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James Davis McGee

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EVALUATION OF STRENGTH PROPERTIES OF SEVERAL SOILS TREATED WITH VARIOUS ADMIXTURES

A THESIS

Presented to

the Faculty of the Graduate Division

by

James Davis McGee

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EVALUATION OF STRENGTH PROPERTIES OF SEVERAL

SOILS TREATED WITH VARIOUS ADMIXTURES

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I wish to express my appreciation to Professor R. J. Paquette for his guidance throughout this project, to Professor G. F. Sowers and Dr. A. Vesic for instilling the desire and providing the background for this work. An especial note of appreciation is due also for my wife, Eve, for her encouragement and loyal assistance.

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ABSTRACT

EVALUATION OF STRENGTH PROPERTIES OF SEVERAL SOILS TREATED WITH VARIOUS ADMIXTURES

James Davis McGee

75 pages

Directed by Professor Radnor J. Paquette

In order to meet the demands of an expanding economy and a tremendous increase in vehicles, highway engineers are confronted with the problem of building and maintaining better highways which will withstand the greater traffic and increased loads. These high quality highways require greater stability and strength in the load supporting portions of the roadway. In many locations, suitable soil for the base course and subgrade is not available, creating a problem of transporting suitable soils to the area or changing the physical properties of the available soils by stabilization with admixtures.

This work was undertaken to study various soils and evaluate the effectiveness of stabilization with various admixtures. Used in this study were five selected soils of widely varying physical properties. Using compressive strength to evaluate stability, these soils were stabilized with portland cement, a lime and flyash mixture, phosphoric acid, and asphaltic cutback, RC-3.

Each soil was mixed with the individual admixtures and moisture-density tests were performed to determine the effect on the maximum dry

density and optimum moisture. Using this density and moisture data, samples 2.8 inches in diameter by 5.6 inches in height were statically compacted, and cured for 7 and 28 days. These samples were then tested by an unconfined compression test and a triaxial test using a lateral pressure of 20 psi. Additional samples of the soil-portland cement mixture were tested with a lateral pressure of 50 psi for plotting Mohr's diagrams to determine the effect of that stabilizer on the "angle of internal friction" and "cohesion."

Results of the study indicate that phosphoric acid slightly increased the density in all soils. Portland cement, lime-flyash and RC-3 increased the density in the uniformly graded soils. There was little effect from the addition of portland cement or RC-3 in the well-graded soils while lime-flyash caused a marked reduction in density in these soils.

Strength tests indicated that portland cement was the most effective stabilizer in all soils giving high strength gains. The addition of portland cement also increased the "angle of internal friction" and "cohesion." The lime-flyash admixture and phosphoric acid caused slight strength increases in all soils. Some soils had a negligible strength increase with the addition of RC-3, while other soils indicated a reduction in strength.

CHAPTER I

INTRODUCTION

General.---Soil stabilization with portland cement and other admixtures has become of great importance in recent years. In order to stay abreast of the expanding economy and tremendous increase in vehicles and vehicle-miles traveled each year, highway engineers are confronted with the problem of building and maintaining more and better roads. This problem is not only concerned with shorter and faster routes but also with roads which must be able to withstand the loads imposed by larger and heavier truck traffic. Stabilization has aided the engineer in solving these problems.

A basic requirement in constructing high quality roads is providing a base course of sufficient strength to distribute the high intensity load applied to the pavement to a smaller stress which can be supported by the weaker subgrade. For the stability necessary for this load distribution, a base course soil mixture should be composed of aggregate which is strong and durable enough to resist weathering and crushing, and soil fines of a character such as to provide graded mixtures with sufficient cohesion to act as a binder but without the risk of detrimental volume change. Some areas do not have an available supply of soil meeting the above requirements; therefore the engineer is confronted with the problem of transporting suitable soil into this area or attempting to change the characteristics of the available soil by artificial methods. This artificial changing of the physical properties of a soil is termed "soil stabilization."

This research was undertaken to study various soils and to evaluate the effectiveness of stabilization with various admixtures. The five soils selected were typical soils found in Georgia. The admixtures chosen for comparative purposes were portland cement, asphaltic cutback, phosphoric acid, and a combination of lime and flyash. The use of portland cement as a stabilizing agent has increased tremendously since the first controlled soil-cement project was constructed in South Carolina about 1933, and it is probably the most widely used admixture today. Bituminous materials have had considerable use as stabilizers, especially in fine sands. The cutback, RC-3, used in this study has been successfully used in many areas. Phosphoric acid is a relatively new product in the field of stabilization but it has shown some stabilizing qualities in experimental work. The combination of lime and flyash has shown some success in this field but it, too, is relatively new.

The criteria used to evaluate these admixtures was the compressive strength, which was determined by both an unconfined compressive test and a triaxial test using a lateral confinement of 20 psi. The tests were performed on the samples after a curing period of 7 and 28 days. Additional work was done with the various soils combined with portland cement to evaluate effects of this admixture on cohesion and angle of internal friction.

Previous studies.--In 1935, the Portland Cement Association began a program of investigation in an attempt to determine the basic principles controlling mixtures of soil and portland cement. This basic research by Catton (1)* on various soils mixed with cement to produce satisfactory

---

*Numbers in parentheses refer to the corresponding numbers in the bibliography.

durability and stability was based on wet-dry and freeze-thaw tests. Conclusions from that work indicated certain soil characteristics were necessary, namely:

1. Liquid Limit must be below 50 per cent.
2. Plastic Index must be below 25 per cent.
3. Clay content must not exceed 35 per cent.
4. Percentage of solids at maximum density must be 60 or greater.
5. The particular soil must possess a "regular" moisture-density curve.

Later, work by Winterkorn (2) showed that theoretical and experimental evidence permits the conclusion that satisfactory waterproofing and cementing can be accomplished with soils not previously recommended for soil-cement practice.

Felt (3) described the factors that have a pronounced influence on the physical properties of soil-cement as the soil type, quantity of water and cement added, density to which the mixture is compacted, mixing time and degree of pulverization of the soil. Goecker, et al. (4) described a study of several variables on the unconfined compressive strength of lime-flyash stabilized soils, the effect of the mixture on standard Proctor moisture-density relationship and an evaluation of the resistance of lime-flyash stabilized soils to freezing-thawing and wetting-drying. Minnick and Williams (5) described several field projects of lime-flyash soil mixtures with a comparison of performance and properties of the mixtures.

The American Road Builders' Association Committee on Soil-Asphalt Stabilization (6) discussed the uses of various asphaltic products in stabilizing sandy and cohesive soils. They described the different problems involved in stabilizing the two types of soils and suggested specifications and construction procedures. Benson (7) reported on the proper use of bituminous materials for soil stabilization. Lyons (8) described some work with phosphoric acid as a stabilizer. This work showed that soil stabilized with about two per cent phosphoric acid became less plastic, was easier to mix and increased the strength of the mix.

With this and other research work as a background, this study was undertaken to evaluate the comparative stabilizing qualities of these four admixtures with several different soils.

CHAPTER II

MATERIALS AND TEST EQUIPMENT

Soils.--The soils chosen for this study are typical of the available roadbuilding soils in the general area from which they were obtained. All soils were obtained from within the state of Georgia. Soil I is a brownish, well-graded, clayey, silty sand; Soil II is a reddish brown, uniform, silty, clayey sand; Soil III is a greyish-white uniform sand; Soil IV is a red, well-graded, silty, sandy clay; and Soil V is a yellowish-brown, well-graded clayey, silty sand. A description of the soils is given in Table 1, with the grain size distribution shown in Figure 1.

According to the Georgia Highway Department classification and usage, only Soil II would be suitable for base construction without treatment with aggregate or an admixture. Soils I, III and IV would be suitable for subgrade construction without treatment while Soil V would require treatment before using as a subgrade and would not normally be used for base construction even with treatment. It is noted from Table 1 that although Soils I and II have the same classification under the Bureau of Public Roads Classification, these two soils are vastly different in appearance, texture and stabilizing characteristics. Physical testing of Soil V indicates a granular material, but this soil is a disintegrated rock soil which is very soft and the granular structure is easily broken down which makes this a very poor soil for road construction.

Table 1. Description of Soils

Soil No.	I	II	III	IV	V
Location by County	Carroll	Effingham	Camden	Fulton	Fulton
Textural analysis % retained by wt.					
Sieve No. 10	3	0	0	3	2
Sieve No. 40	14	54	2	19	24
Sieve No. 60	37	68	7	28	36
Sieve No. 100	44	74	53	37	46
Sieve No. 200	62	83	92	46	55
Total Silt, %	21	2	3	22	24
Total Clay, %	6	11	--	27	14
Specific Gravity	2.67	2.63	2.69	2.70	2.69
Liquid Limit	13	14	--	29	37
Plastic Limit	--	--	--	23	--
Plastic Index	NP	NP	NP	6	NP
BPR Classification	A-2-4(0)	A-2-4(0)	A-3-(0)	A-4-(4)	A-4-(2)
Ga. Hwy. Dept. Classification	C-1 Topsoil	A-1 Topsoil	A-1 Subgrade	1-B Embankment	II-A Embankment

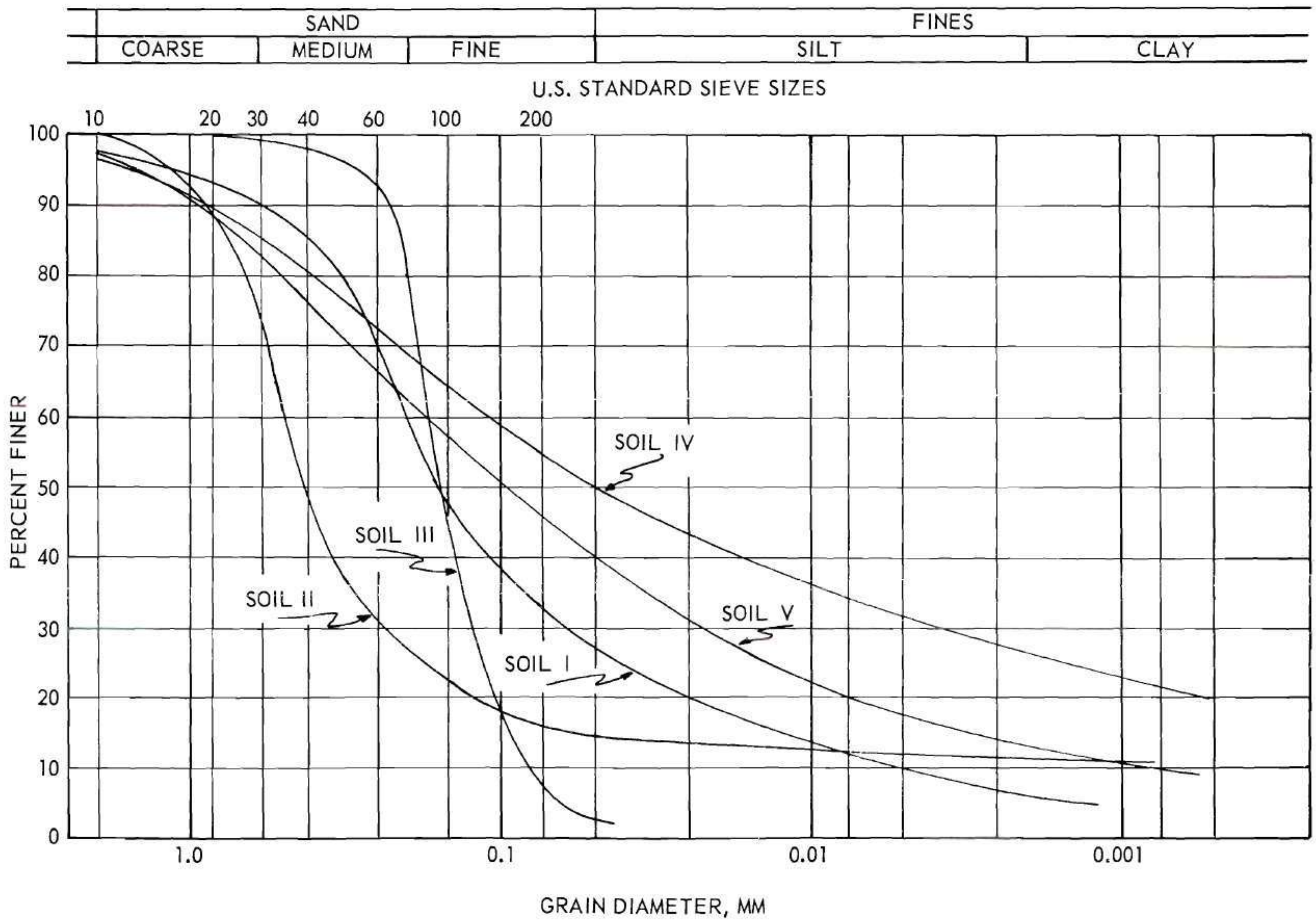

Figure 1. Grain Size Distribution.

Admixtures.--The portland cement used was Type I normal purchased on the open market. A typical analysis of the several sacks used is shown in Table 2.

The asphalt used in the study was an asphaltic cutback RC-3.

The lime used in the mixture of lime and flyash was a hydrated high calcium lime purchased on the open market. Analysis of the flyash is shown in Table 3.

The phosphoric acid used was an 85 per cent solution.

Test Equipment.--The moisture-density tests were performed with the Standard Proctor compaction equipment consisting of a mold of 1/30 cubic foot volume and compacted with a 5.5 pound hammer falling 12 inches with the soil compacted in 3 layers with 25 blows on each layer.

The molding equipment consisted of an eight inch length of steel tubing bored to 2.8 inches in diameter with a 3 inch extension attached to the top to retain the loose mixture and a split 3 inch spacer on the bottom to support the mold while filling. Compacting the mixture in the mold was a 4 inch removable piston used in the bottom and a 7 inch piston for the top which was attached to the upper movable head of the testing machine. A dial gage was mounted on the end of a measured rod for determining the proper height of the compacting mix. Application of load for compaction was from a 120,000 pound constant-strain testing machine. The molding equipment and molding processes are shown in Figures 2 and 3 respectively.

For strength determination, the sample was placed in a standard type triaxial cell. Lateral pressure, when used, was provided by compressed air metered into the sealed cell. Load was applied through a

Table 2. Portland Cement Analysis

Chemical Composition, %	
Silicon dioxide, SiO_2	20.46
Ferric oxide, Fe_2O_3	2.44
Aluminum oxide, Al_2O_3	5.90
Sulphur trioxide, SO_3	2.08
Calcium oxide, CaO	62.87
Magnesium oxide, MgO	4.18
Insoluble residue	0.30
Loss on ignition	1.38
Specific surface area, Blaine (sq. cm/gm)	3464

Table 3. Flyash Analysis

	Macon, Ga.	Columbia, S. C.
Chemical composition, %		
Silicon dioxide, SiO_2	41.40	45.92
Aluminum oxide, Al_2O_3	21.05	32.00
Ferric oxide, Fe_2O_3	8.65	16.50
Magnesium oxide, MgO	5.36	1.40
Sulphur trioxide, SO_3	1.16	0.84
Carbon, C	1.66	2.32
Loss on ignition	3.12	2.24
Specific surface area, Blaine (sq. cm/gm)	3427	1760

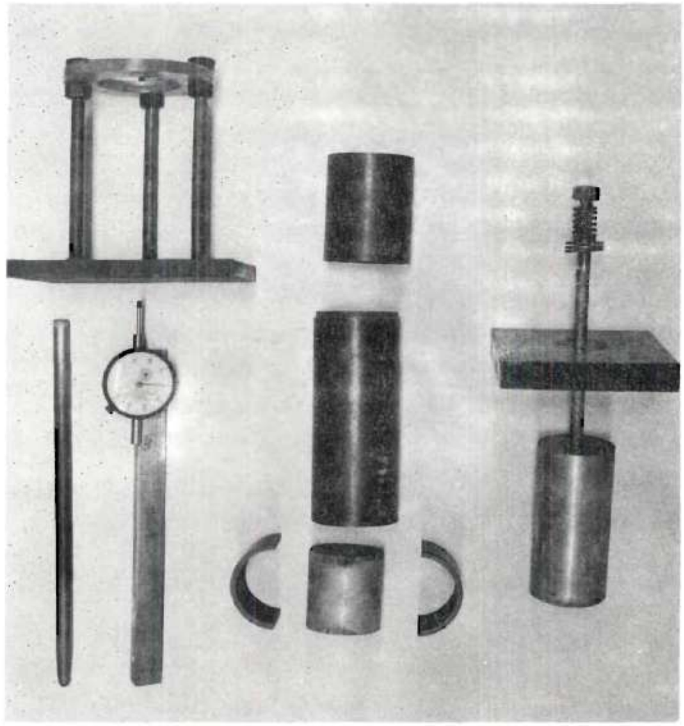

Figure 2. Molding Equipment.

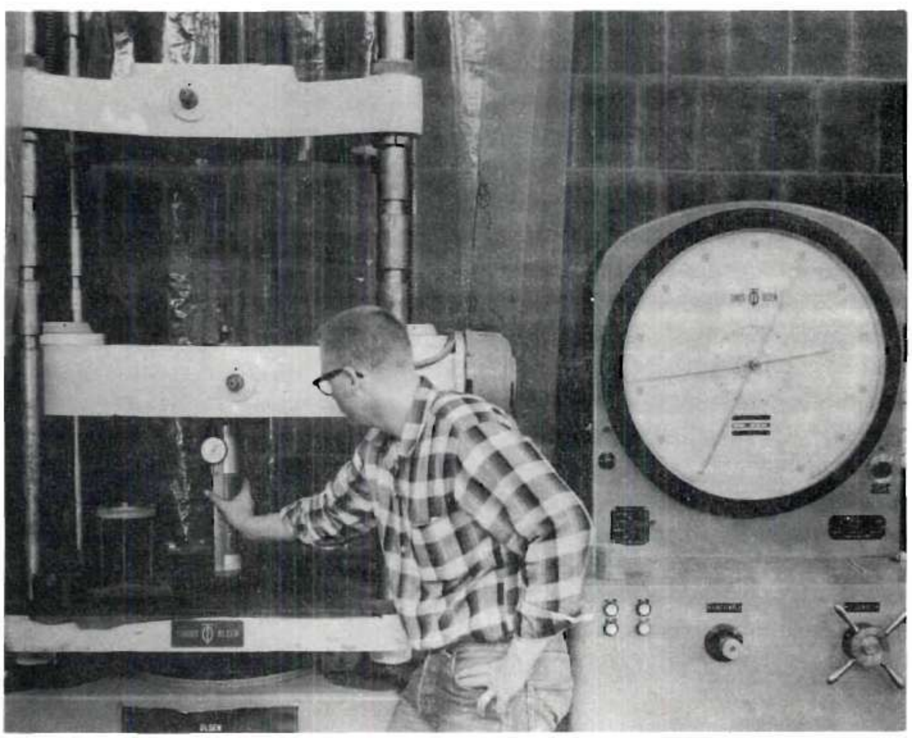

Figure 3. Molding Soil-Specimen.

piston in the top of the cell by a 30,000 pound constant strain type testing machine, or in some cases, samples were tested in the standard triaxial cell using a constant stress scales-type loading device. The constant strain and constant stress triaxial testing equipment is shown in Figures 4 and 5 respectively. Strain measurements were made with a dial gage attached to the top of the triaxial cell.

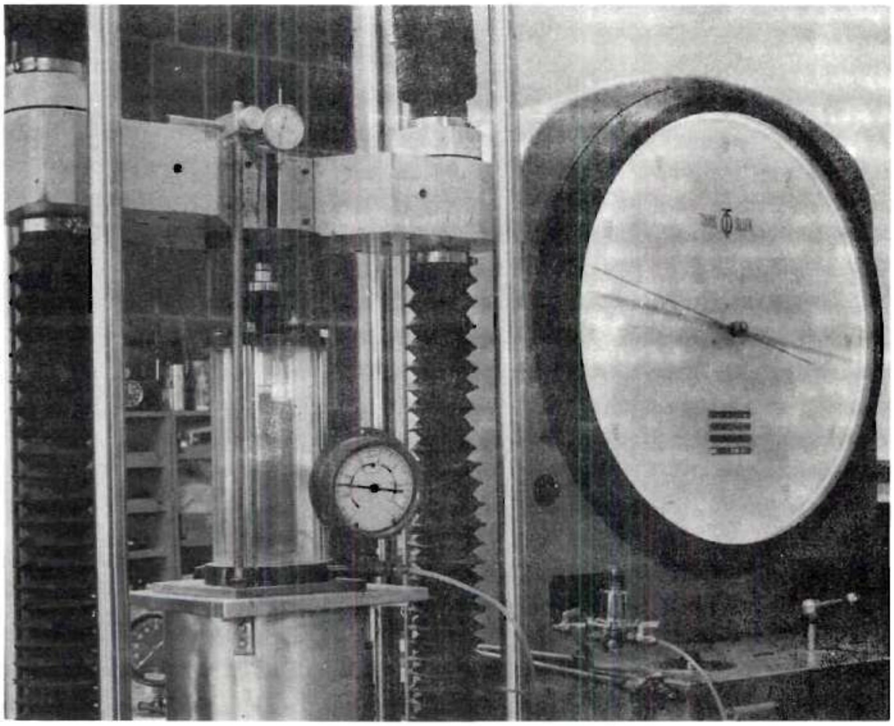

Figure 4. Constant-Strain Triaxial Equipment.

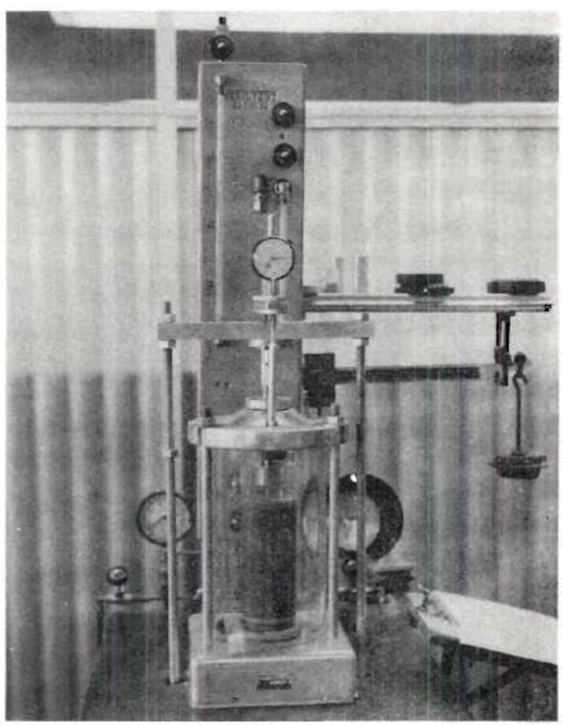

Figure 5. Constant-Stress Triaxial Equipment.

CHAPTER III

TESTING PROCEDURES

General.--The basic testing program was designed to evaluate the compressive strength of different types of soils mixed with various admixtures. The procedures adopted were for testing material passing a No. 4 sieve. Some of the desirable features in a testing program of this nature include:

1. A standard size sample and method of compaction which is suitable for testing various type soils.
2. A method of curing which is comparable to field curing conditions.
3. Evaluation by testing the stability of the samples under conditions which can be correlated to actual field conditions of stability failures.
4. Consistency in reproducing test results.

Preparation of soil and mixing.--The soil was air-dried to a uniform moisture content and sieved through a No. 4 sieve with only the material passing being used in the tests. All the soils were predominantly minus 4 materials, with the majority of the discarded material being hardened lumps and roots.

Mixing was done in a Hobart Model C-100 mixer at a speed of 144 RPM. For soils with a dry mixture, the dry ingredients were mixed one minute, the water for the proper moisture content was added and then mixed for 9 minutes. For the mixture with phosphoric acid, the acid was combined with the water and mixed for 10 minutes. The mixture with the asphalt was first mixed for 3 minutes with the proper amount of moisture; then the asphalt was added and the mixing continued for 7 more minutes.

Moisture-density tests.--Moisture-density tests were performed on each soil with no admixture and with each soil combined with the various test increments of stabilizer. All tests were performed in accordance with standard ASTM and AASHO specifications. Tests using cement as an admixture were made at 2 per cent increments up to 12 per cent on all soils except Soil III. Due to the character of this soil, tests were made at 4 per cent increments of cement up to 12 per cent. Moisture-density tests were also made on all soils with the other admixtures at the various test increments. An exception was that no moisture-density test was made with Soil III and phosphoric acid.

Molding test specimens.--Molding of all the soils and mixtures was done immediately after mixing except when RC-3 was used as an admixture. The soil and RC-3, after mixing, was allowed to stand in the open air until it had a "tacky" feeling. Molding was done with static compaction in the 2.8 inch diameter mold compacting the soil mixture to a height of 5.6 inches. With the bottom piston placed in the mold and spacers and extension attached, the properly mixed soil or soil and admixture was placed in the mold in two layers, each layer being rodded 20 strokes with the 5/8 inch rod. The amount of material placed in the mold was a predetermined weight calculated to give the maximum density, as determined from the moisture density curve, when the sample was compacted to a height of 5.6 inches. The spacers were then removed and the mold placed in alignment with the top piston which was fixed to the upper head of the loading machine. The two pistons were forced together until the dial gage indicated the proper 5.6 inch height. Loading pressure was then released, the lower piston was removed and with the mold placed on the extruding jack, the sample was extruded from the mold. After extruding, the height and weight of the sample was checked.

Each batch consisted of material for 4 samples. Two moisture content samples were taken from each batch and checked after oven drying. A tolerance of ±1 per cent was allowed in the moisture content.

In developing the test procedure other sample sizes and compaction methods were attempted but all eliminated because of certain shortcomings. Primary consideration was given to the Standard Proctor method of compaction (ASTM Method D-558-44). This method, being more or less standard for all compaction work, would be ideally suited for correlation of past tests but the sample size was unsuitable. Past studies (9) (10) have shown that a sample having a ratio of length to diameter of approximately two is necessary to overcome the effects of end restraint during the triaxial test. On the Proctor size samples with an l/d ratio of approximately one, this end restraint caused serious errors in the strength measurement. An attempt was made to trim the samples to a 1.4 inch diameter but this proved inadequate due to the scaling of the granular soil samples and the greater amount of time involved.

Another method considered was the miniature compaction equipment developed by Professor George F. Sowers in the Georgia Institute of Technology Soils Laboratory. This method consists of a 2.8 inch diameter by 6.3 inch high mold with compaction accomplished with a 5 pound hammer dropping 12 inches using 25 blows on each of 4 layers. The density obtained very closely approximates the density determined by ASTM D-559-44.

Difficulties encountered with this method occurred from the compaction planes which were formed at each layer of soil. These planes caused non-uniformity in density of the compacted samples which caused, in many cases, a low strength determination when the sample sheared along the compaction plane.

Curing.--In adopting a method of curing the test samples, primary consideration was aimed at approximating field conditions. In this respect, experience has indicated that the moisture content of a compacted highway base course will undergo very little change under normal curing conditions, i.e., unless the roadway is inundated or subjected to extreme wet or dry conditions. To approximate normal curing conditions and prevent moisture changes due to the atmospheric conditions, the test samples were placed in polyethylene freezer bags and sealed immediately after molding. The samples were then placed in a moisture room (approximately 90 per cent relative humidity and 70° F.) to prevent any variation from daily fluctuations in temperature and humidity.

Testing specimens for compressive strength.--Samples were cured for 7 and 28 days and then tested in a dry condition as they were removed from the freezer bags.

Compressive strength values of the molded samples were obtained by both the unconfined compression test and the triaxial test using a lateral confining pressure of 20 psi. Twenty-eight day samples of each soil with no admixture and with 6, 9, 12 and 15 per cent portland cement were also tested triaxially using a confining pressure of 50 psi.

After the specified curing period, the samples were removed from the sealed bags and weighed to check for any moisture changes. All samples were tested in a dry condition. Both the unconfined and confined tests were made with the sample in a standard triaxial cell of approximately 6 inches diameter and 10 inches height. In the case of the confined tests, the sample was enclosed in a thin rubber membrane and the cell sealed in order to apply the lateral pressure by compressed air.

Loading was accomplished on either a scales-type test apparatus or on a constant-strain screw type testing machine. A dial gage was placed on the loading piston and strain readings taken at various load increments. On the constant-strain test, a rate of loading of 0.05 inches of movement of the loading head per minute was used. With the test on the scales-type apparatus, loads were applied at the rate of an increment of load every 30 seconds with the increment varied to approximate 10 per cent of the ultimate load. No variations were noted from using the two types of loading equipment with the two different rates of loading. Loading was continued until the sample sheared or in the case of bulge failures, the stress-strain relationship indicated a horizontal curve. After this load was ascertained the sample was removed from the triaxial cell and a moisture sample taken for check purposes.

CHAPTER IV

EVALUATION OF TEST RESULTS

General.--Testing of the various soils and soils combined with the admixtures involved determining maximum density and optimum moisture and compressive strength. Compressive strength data of the soils and soil-portland cement mixtures were also evaluated to determine the cohesion and angle of internal friction.

Each of the five soils used in this study was combined with portland cement in increments of 2 per cent ranging from 2 to 12 per cent. Each soil was combined with a mixture of lime and flyash on a basis of 75 per cent soil and 25 per cent lime-flyash. The lime and flyash proportions in this 25 per cent was varied by ratios of lime to flyash of 1:1, 1:2, 1:5 and 1:9. The RC-3 admixture was used in percentages of 3, 5 and 7. Phosphoric acid was added in 1 and 2 per cents. All percentages of admixture were based on the dry weight of the soil.

Moisture-density.--A moisture-density curve was plotted for each soil with no admixture and for each soil with the test increments of admixture as noted above. An exception was Soil III, which was tested at 4 per cent increments of portland cement and no moisture-density tests were made on this soil with phosphoric acid as an admixture.

Tables 4 through 8 show the maximum density and optimum moisture as used in molding the samples. Values of percentages of portland cement and Soil III that were not tested were interpolated. Density and moisture

Table 4. Maximum Dry Density and Optimum Moisture for Soil I

Admixture	Maximum Dry Density	Optimum Moisture
	(lb/ft^3)	(%)
None	121.0	9.0
Cement, %		
2	122.9	10.0
4	123.0	10.5
6	123.1	11.0
8	123.9	10.8
10	123.7	10.4
12	124.9	10.5
Lime-flyash, ratio		
1:1	114.3	13.5
1:2	112.1	14.0
1:5	111.0	13.7
1:9	108.6	14.0
Phosphoric acid, %		
1	124.2	9.3
2	125.4	9.0
RC-3, %		
3	123.0	8.7
5	123.2	8.4
7	123.0	6.4

Table 5. Maximum Dry Density and Optimum Moisture for Soil II

Admixture	Maximum Dry Density	Optimum Moisture
	(lb/ft^3)	(%)
None	119.1	10.3
Cement, %		
2	120.1	11.0
4	121.9	11.0
6	122.7	10.2
8	123.1	10.6
10	123.3	10.6
12	123.9	10.1
Lime-flyash, ratio		
1:1	118.7	10.8
1:2	119.8	10.3
1:5	120.5	10.2
1:9	120.8	10.4
Phosphoric Acid, %		
1	124.9	10.5
2	125.6	9.4
RC-3, %		
3	121.9	9.5
5	121.5	8.0
7	119.1	8.5

Table 6. Maximum Dry Density and Optimum Moisture for Soil III

Admixture	Maximum Dry Density	Optimum Moisture
	(lb/ft^3)	(%)
None	101.0	9.5
Cement, %		
2	102.1	9.8
4	104.3	10.0
6	106.5	10.8
8	109.0	11.7
10	110.0	11.4
12	111.1	11.2
Lime-flyash, ratio		
1:1	114.4	11.0
1:2	112.8	11.5
1:5	109.1	12.1
1:9	108.2	13.0
Phosphoric Acid, %		
1	Used same as no Admixture	
2		
RC-3, %		
3	107.2	12.5
5	107.4	11.0
7	109.0	10.0

Table 7. Maximum Dry Density and Optimum Moisture for Soil IV

Admixture	Maximum Dry Density	Optimum Moisture
	(lb/ft^3)	(%)
None	114.2	14.6
Cement, %		
2	112.4	15.5
4	111.6	16.6
6	111.8	16.8
8	112.3	15.8
10	112.2	15.9
12	114.2	15.1
Lime-flyash, ratio		
1:1	101.0	20.0
1:2	102.1	19.8
1:5	102.0	20.0
1:9	102.0	20.0
Phosphoric Acid, %		
1	115.8	15.2
2	117.2	14.5
RC-3, %		
3	114.5	14.0
5	114.1	12.3
7	113.2	12.6

Table 8. Maximum Dry Density and Optimum Moisture for Soil V

Admixture	Maximum Dry Density	Optimum Moisture
	(lb/ft^3)	(%)
None	111.2	16.5
Cement, %		
2	111.9	16.4
4	111.9	16.7
6	111.7	17.0
8	111.2	17.3
10	111.8	16.8
12	111.2	17.3
Lime-flyash, ratio		
1:1	101.5	20.2
1:2	102.0	20.0
1:5	101.3	19.8
1:9	101.4	19.7
Phosphoric Acid, %		
1	115.8	15.9
2	117.4	14.7
RC-3, %		
3	113.3	13.5
5	112.3	13.7
7	111.5	13.7

values used for Soil III and phosphoric acid were the same as for no admixture in that soil. Curves showing the variation in maximum dry density and optimum moisture versus admixture are shown in Figures 6 through 10.

For Soil I, the addition of portland cement produced an increase in maximum density with increasing amounts of cement while the optimum moisture increased slightly with the addition of cement then remained nearly the same as the cement percentage increased. Maximum density with phosphoric acid increased for this soil with no change in moisture. Asphalt caused an increase in density which was almost constant with the higher percentages while the moisture dropped with increasing amounts of RC-3. The addition of lime and flyash to this soil caused a marked reduction at the higher lime-flyash ratios. Optimum moisture increased with the addition of lime-flyash, then remained nearly the same as the lime-flyash ratio increased.

Evaluation of Figure 7 for Soil II shows that increasing percentages of cement causes increasing density with little change in optimum moisture. The addition of phosphoric acid caused a substantial increase in density while the higher per cent of acid increased only slightly over the lesser per cent. No appreciable change occurred in the optimum moisture. Addition of RC-3 to this soil increased the density at 3 and 5 per cent while at 7 per cent, the density dropped to the same value as the original soil. Optimum moisture decreased with the RC with the greatest decrease at 5 per cent. Adding lime and flyash to this soil produced a very slight decrease in density at the lowest ratio of lime-flyash with

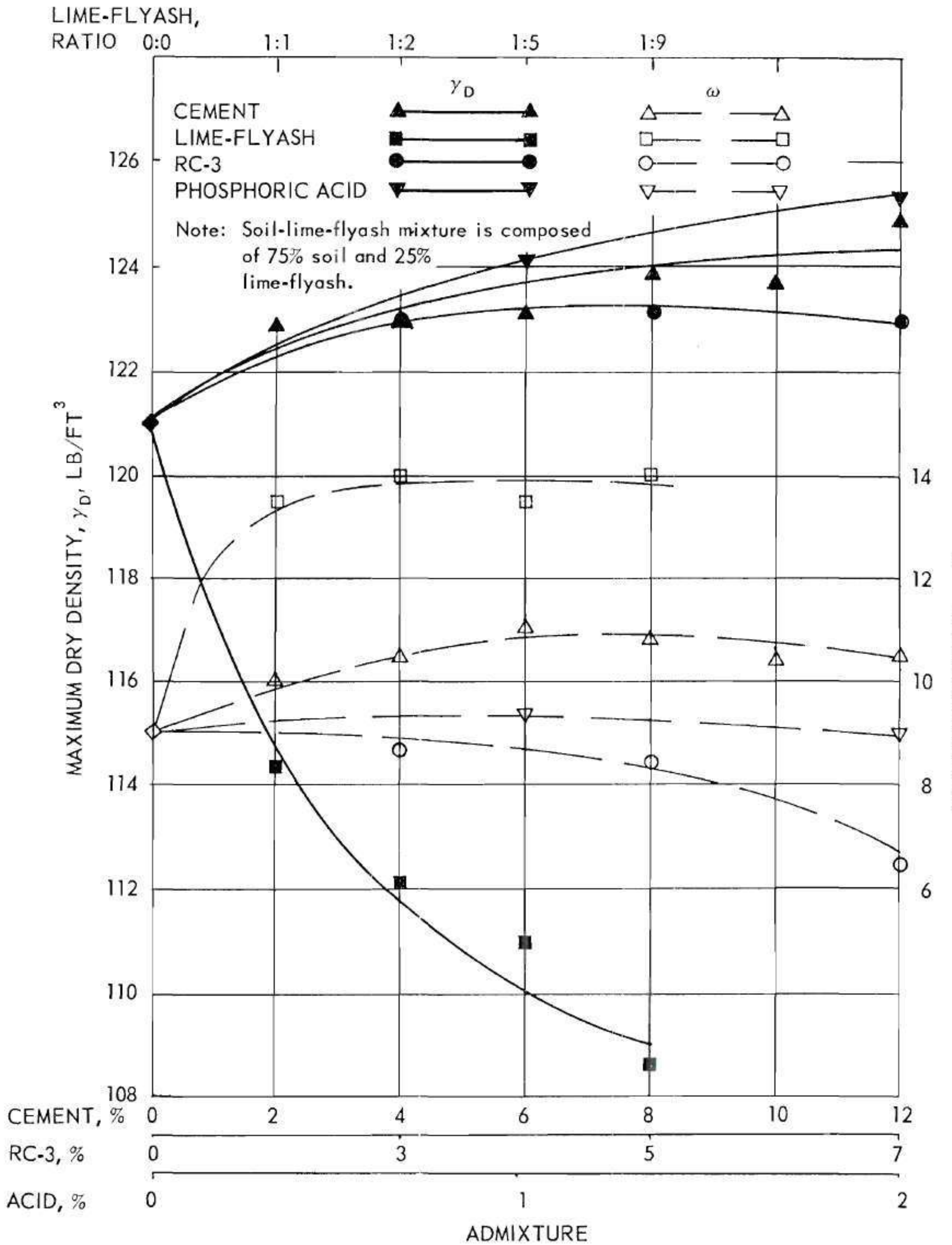

Figure 6. Relationship of Maximum Dry Density and Optimum Moisture Versus Admixture for Soil I.

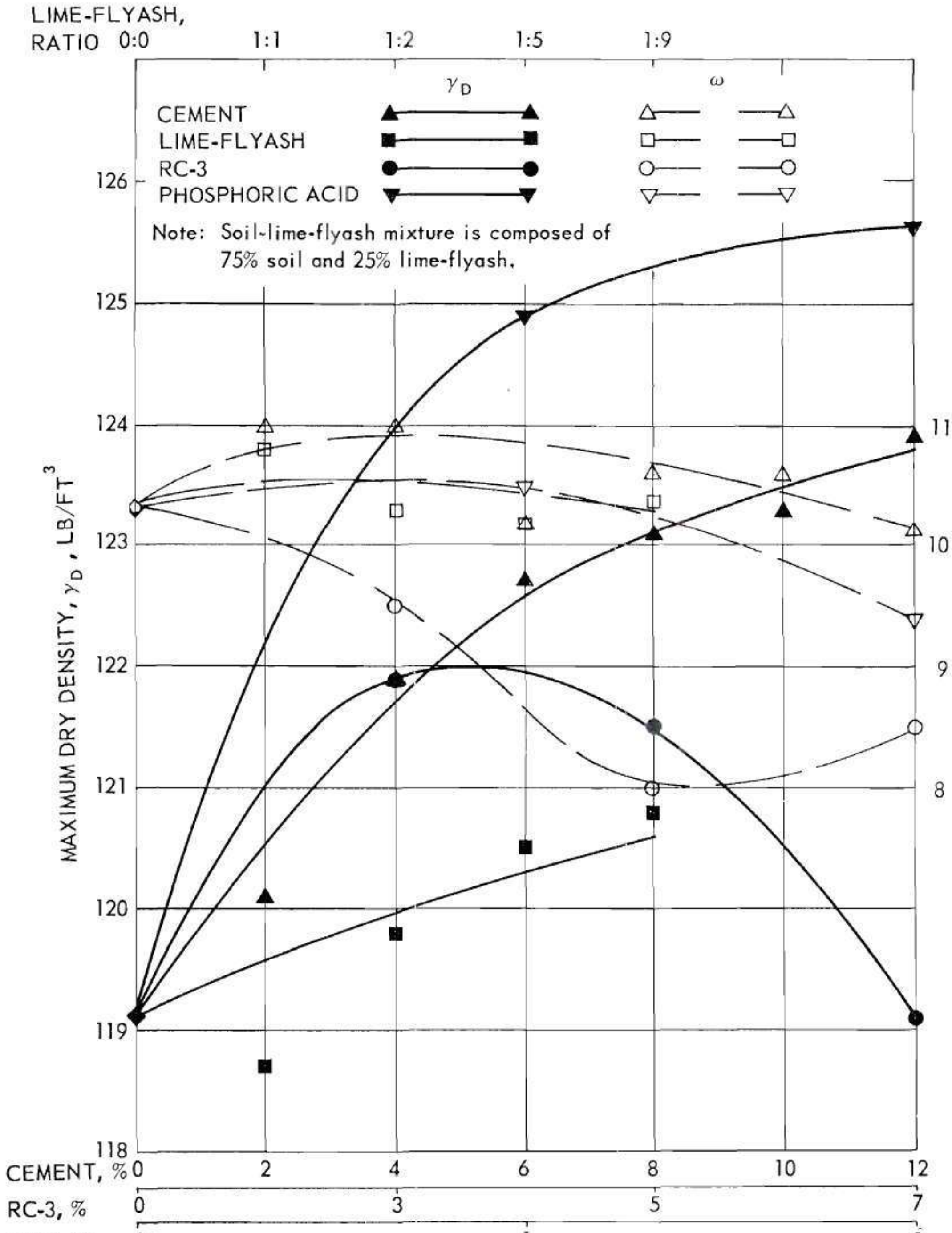

Figure 7. Relationship of Maximum Dry Density and Optimum Moisture Versus Admixture for Soil II.

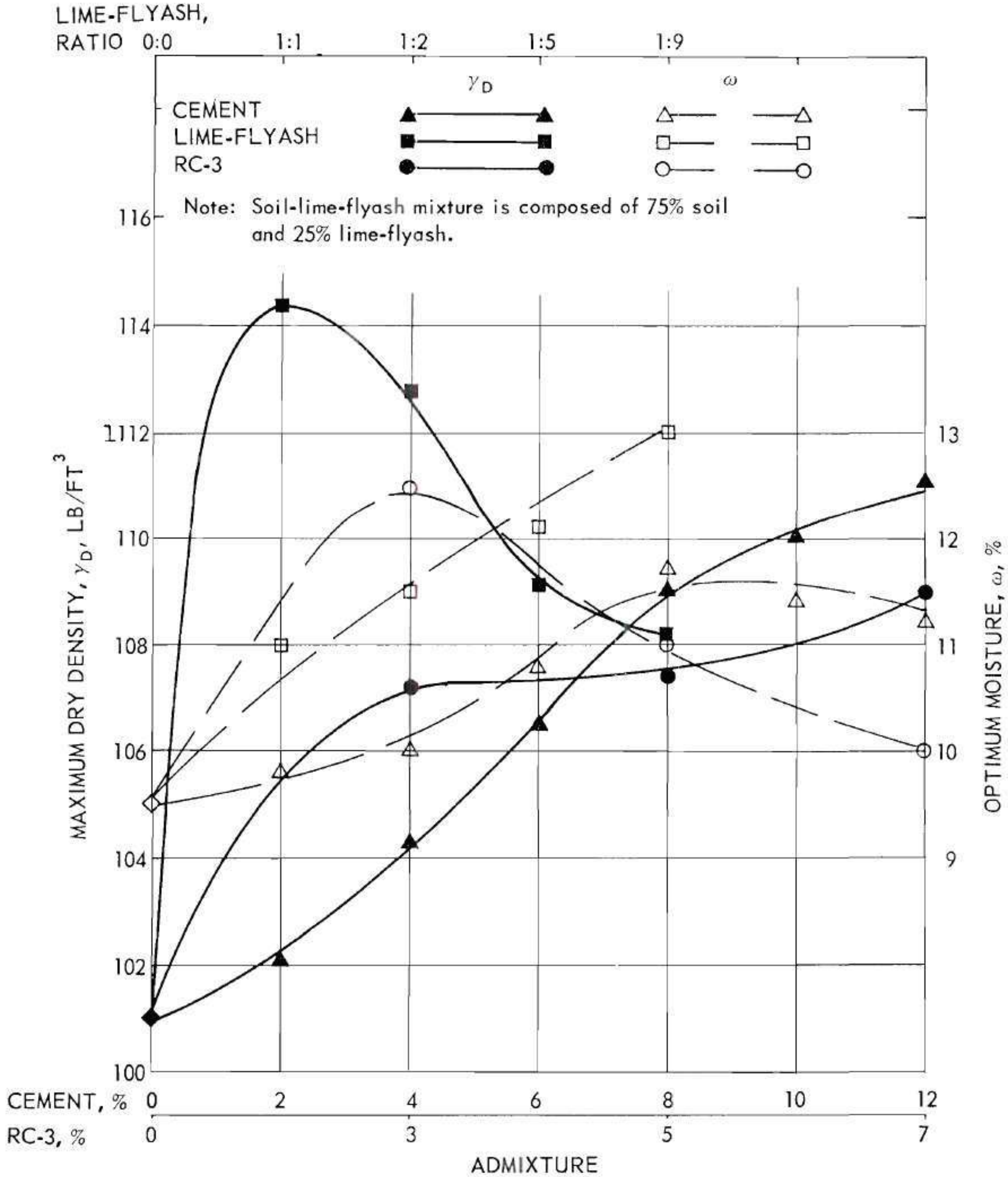

Figure 8. Relationship of Maximum Dry Density and Optimum Moisture Versus Admixture for Soil III.

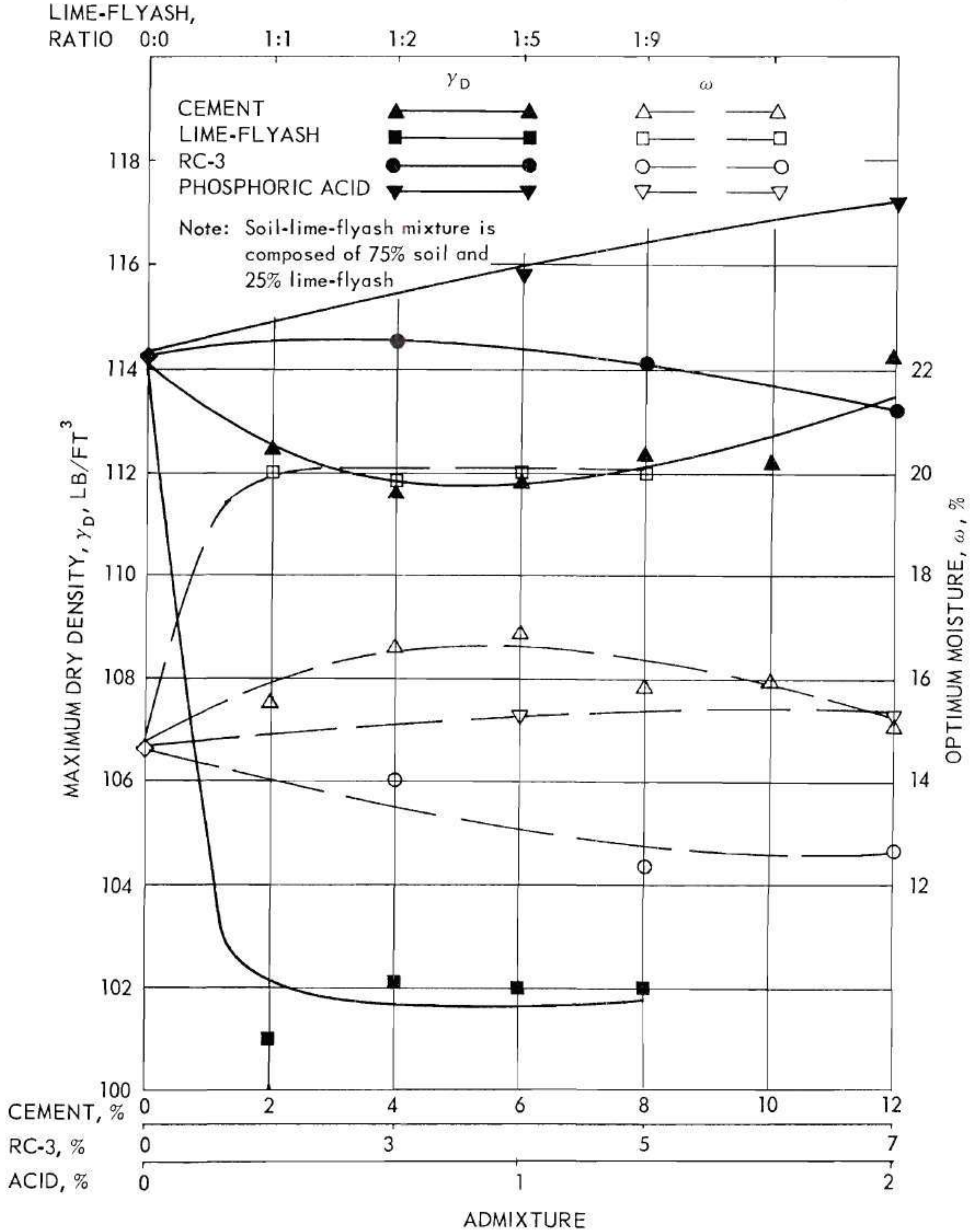

Figure 9. Relationship of Maximum Dry Density and Optimum Moisture Versus Admixture for Soil IV.

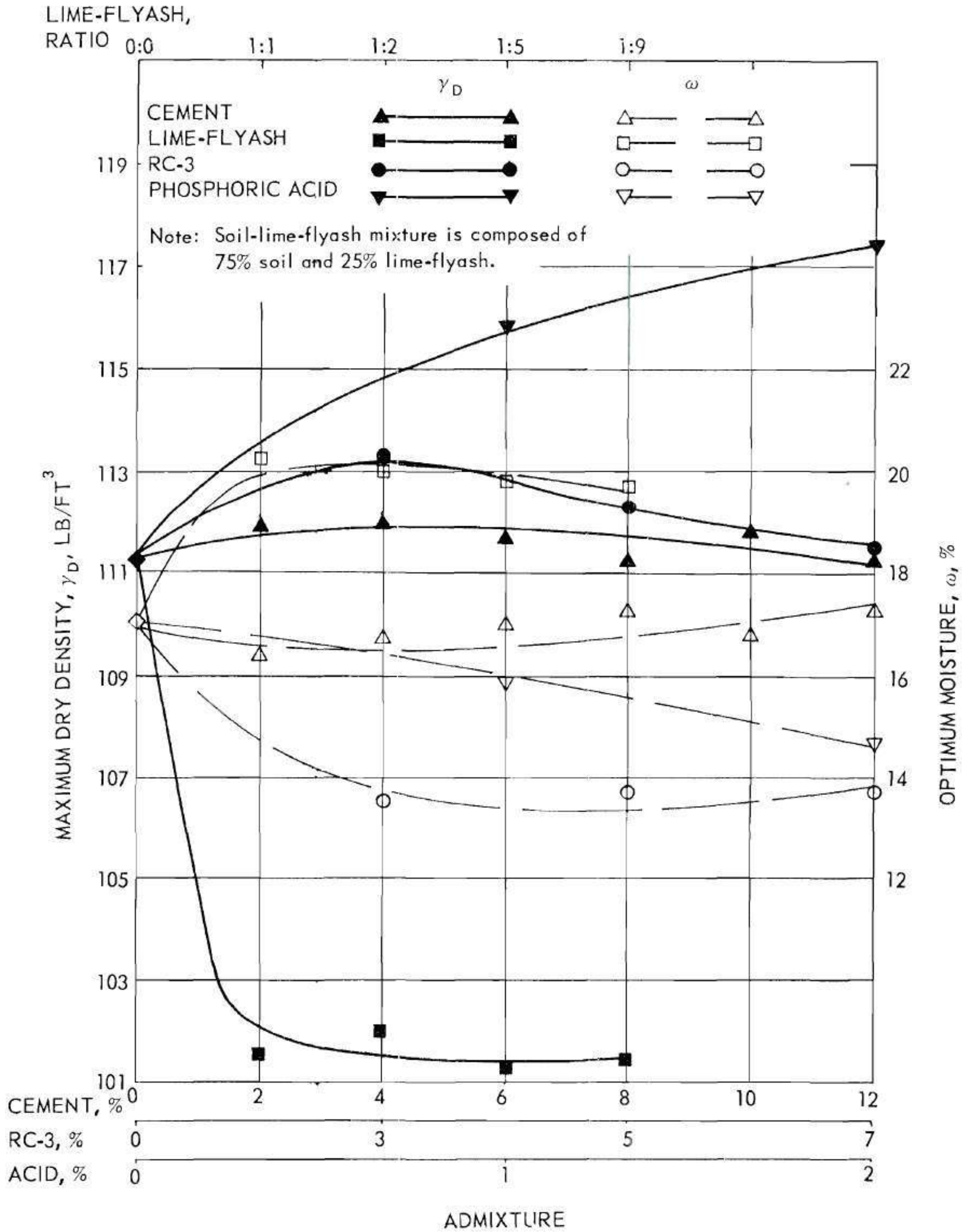

Figure 10. Relationship of Maximum Dry Density and Optimum Moisture Versus Admixture for Soil V.

the density increasing slightly with the higher ratios. Again, optimum moisture was changed only slightly.

Soil III with its fine uniform grains was very difficult to compact as the compaction hammer sheared the soil in the mold. Optimum moisture in this soil was not critical as the compaction could be accomplished over a fairly wide range of moisture contents. The addition of an admixture improved the compaction characteristics. Portland cement as an admixture caused a nearly linear increase in density with increase in percentage of cement. Optimum moisture also increased but to a lesser amount at the higher cement contents. RC-3 produced an increase in density but little change with increase in RC-3 per cent. Optimum moisture increased at 3 per cent RC but then dropped to approximately the original soil value for 7 per cent RC. The addition of the smallest proportion of lime-flyash gave a marked increase in density with a lesser increase as the lime-flyash ratio increased. Optimum moisture for this mixture increased approximately linear with increasing amounts of flyash.

The addition of admixtures to Soil IV had only slight effect on density except the admixture, lime-flyash. Portland cement added to this soil caused a slight reduction in density, the reduction becoming less at the higher percentages. Optimum moisture increased slightly with the intermediate percentages of cement with practically the same moisture content at higher percentages as with the original soil. A small linear increase in density with phosphoric acid was noted with no change in moisture. The only change with this soil and asphalt was a slight decrease in density at 7 per cent and small reduction in moisture with increasing asphalt percentages. With the addition of lime-flyash, a marked decrease in density was noted with a corresponding rise in optimum moisture. Varying the ratio of lime to flyash did not effect this drop in density or rise in moisture.

For Soil V, the addition of portland cement had no effect on density or moisture. Phosphoric acid produced an increase in density with increasing percentages of admixture while the optimum moisture had a corresponding decrease. RC-3 increased the density slightly at 3 and 5 per cent with no change at 7 per cent. Optimum moisture decreased with the RC but no change occurred with varying percentages. Lime-flyash caused a marked reduction in density and a corresponding increase in moisture but the density and moisture values remained nearly constant with varying ratios of lime to flyash.

Compressive strength.--In evaluating the molded samples, only samples molded within 1 per cent of optimum moisture were used. For each test, 4 samples were molded for unconfined compression at 7 and 28 days and 4 samples for triaxial testing at 7 and 28 days. For compressive strength evaluation, only the values which were within 10 per cent of the average of the other samples were used. In most instances, the results were consistent and represent the average of 4 samples tested. Compressive strength results are shown in Tables 9 through 13. Figures 11 through 20 show curves of compressive strength versus admixture for the confined triaxial tests and for the unconfined tests.

As shown in Figures 11 and 12 and Table 9 the compressive strength of Soil I was increased with the addition of admixtures. Portland cement was, by far, the most beneficial admixture with a small gain in strength with low percentages of cement and greater increases in strength with the

Table 9. Compressive Strength for Soil I

Admixture	Compressive Strength, psi 7 Day		28 Day	
	0*	20	0	20
None	15	81	7	81
Cement, %				
2	20	114	23	139
4	50	163	81	239
6	98	254	148	261
8	247	354	274	516
10	431	580	557	693
12	572	726	712	883
Lime-flyash, ratio				
1:1	48	133	57	159
1:2	41	138	36	115
1:5	58	156	74	180
1:9	16	96	25	110
Phosphoric acid, %				
1	14	126	27	133
2	18	95	29	120
RC-3, %				
3	14	53	22	92
5	19	67	35	89
7	26	71	44	90

*Note: The 0 and 20 indicate confining pressure in psi in the triaxial test.

Table 10. Compressive Strength for Soil II

Admixture	Compressive Strength, psi 7 day		28 day	
	0*	20	0	20
None	15	85	13	84
Cement, %				
2	95	189	144	228
4	217	317	220	346
6	378	439	354	488
8	475	565	667	728
10	618	717	880	945
12	769	864	1035	1114
Lime-flyash, ratio				
1:1	128	232	153	277
1:2	115	229	140	266
1:5	88	197	100	224
1:9	72	191	85	205
Phosphoric acid, %				
1	34	126	41	135
2	34	120	47	143
RC-3, %				
3	15	63	16	66
5	30	75	29	70
7	24	53	25	51

*Note: The 0 and 20 indicate confining pressure in psi in the triaxial test.

Table 11. Compressive Strength for Soil III

Admixture	Compressive Strength, psi 7 day		28 day	
	0*	20	0	20
None	0	0	0	59
Cement, %				
2	0	61	3	58
4	3	68	3	62
6	7	89	5	68
8	49	163	128	216
10	122	240	222	329
12	262	324	389	484
Lime-flyash, ratio				
1:1	21	142	14+	106+
1:2	7	108	12+	62+
1:5	9	94	11+	89+
1:9	8+	70+	8+	78+
Phosphoric acid, %				
1	2	70	2	70
2	1	68	2	70
RC-3, %				
3	2	52	2	54
5	2	60	3	66
7	3	69	5	72

*Note: The 0 and 20 indicate confining pressure in psi in the triaxial test.

+These samples were molded with Columbia, S. C. flyash.

Table 12. Compressive Strength for Soil IV

Admixture	Compressive Strength, psi 7 day		28 day	
	0*	20	0	20
None	33	58	38	59
Cement, %				
2	104	142	109	167
4	249	291	274	347
6	272	344	369	465
8	289	367	376	482
10	349	466	458	568
12	457	469	550	640
Lime-flyash, ratio				
1:1	53	128	65	149
1:2	45	116	51	122
1:5	43	108	51	143
1:9	42	108	49	128
Phosphoric acid, %				
1	41	103	46	117
2	78	149	115	182
RC-3, %				
3	34	51	37	57
5	37	54	44	63
7	42	48	44	46

*Note: The 0 and 20 indicate confining pressure in psi in the triaxial test.

Table 13. Compressive Strength for Soil V

Admixture	Compressive Strength, psi 7 day		28 day	
	0*	20	0	20
None	23	38	25	45
Cement, %				
2	73	123	81	133
4	188	245	246	290
6	209	282	291	352
8	268	339	341	417
10	296	382	394	457
12	283	367	413	504
Lime-flyash, ratio				
1:1	48	130	113	199
1:2	44	126	91	177
1:5	34	106	75	152
1:9	37	100	65	143
Phosphoric acid, %				
1	46	77	63	108
2	58	100	82	129
RC-3, %				
3	32	55	33	67
5	31	57	35	68
7	40	65	32	56

*Note: The 0 and 20 indicate confining pressure in psi in the triaxial test.

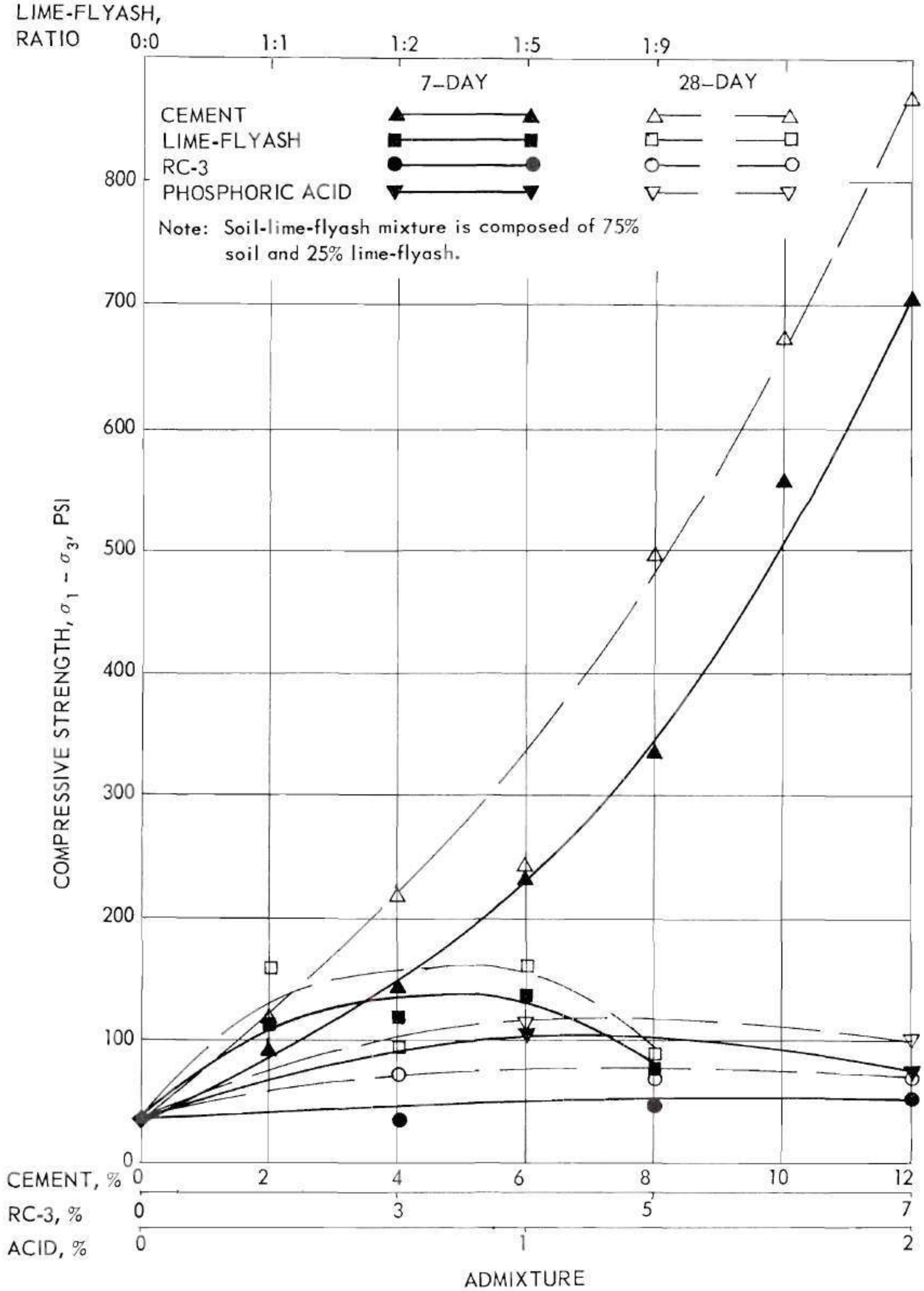

Figure 11. Relationship of Confined Compressive Strength and Admixture for Soil I.

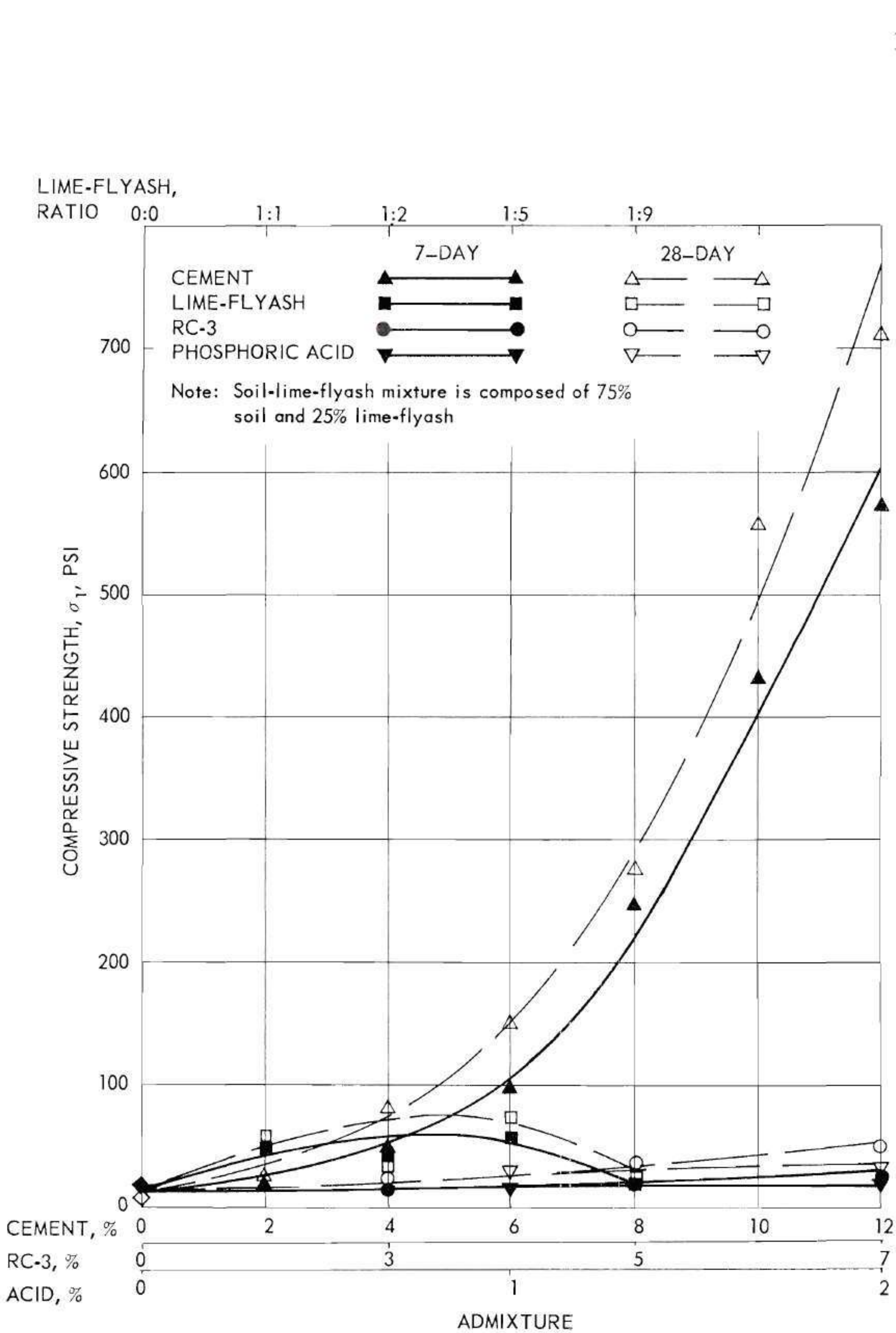

Figure 12. Relationship of Unconfined Compressive Strength and Admixture for Soil I.

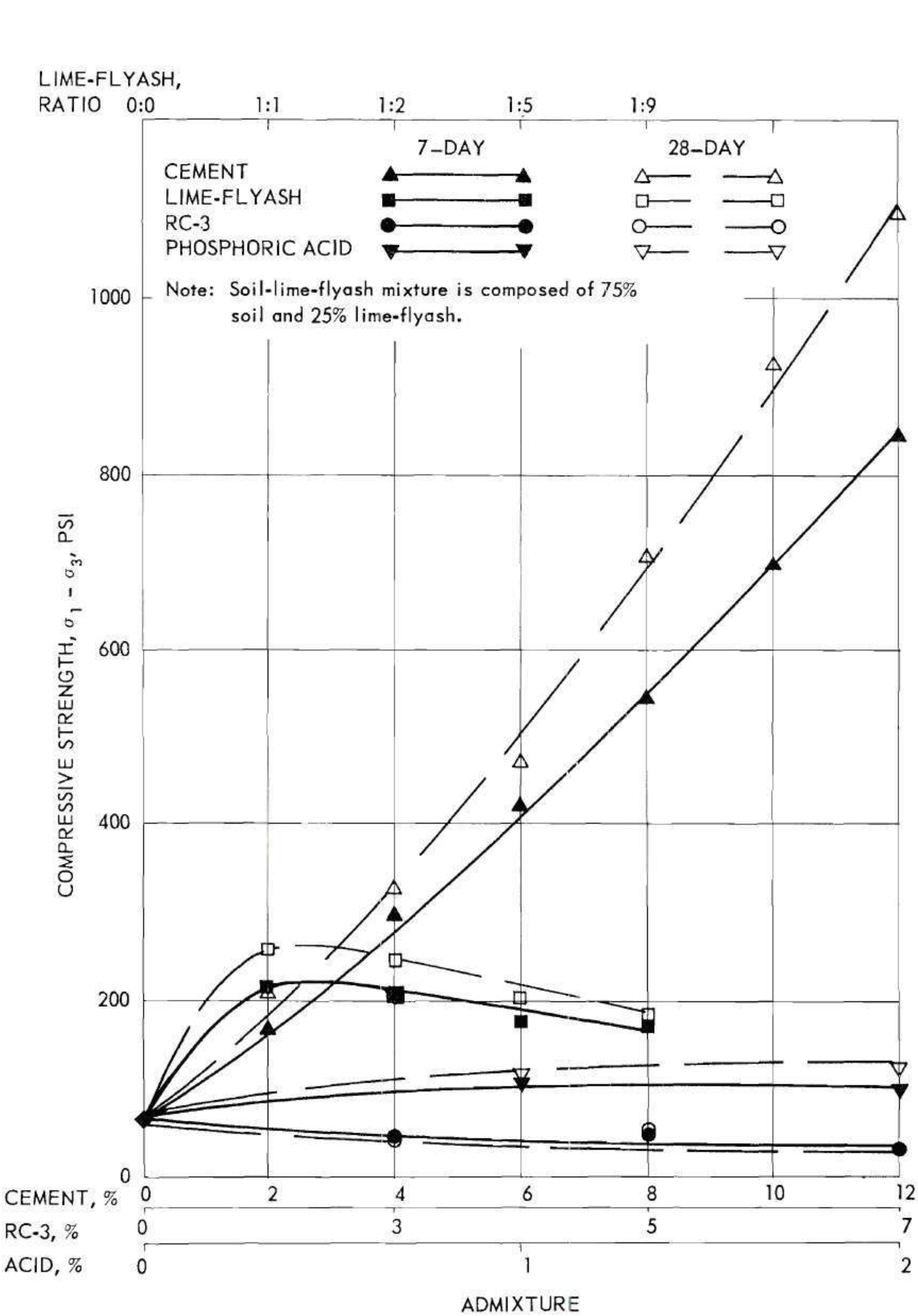

Figure 13. Relationship of Confined Compressive Strength and Admixture for Soil II.

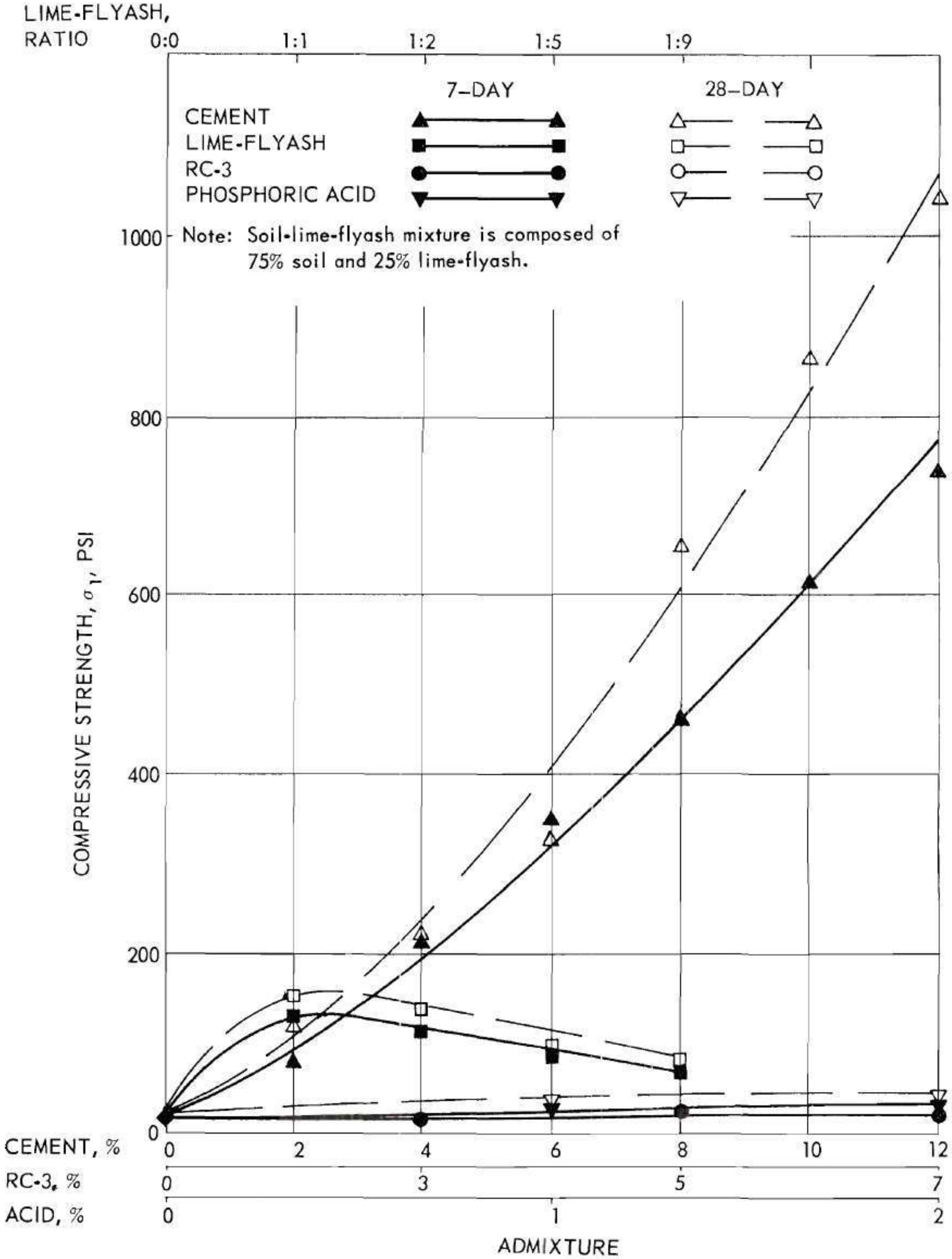

Figure 14. Relationship of Unconfined Compressive Strength and Admixture for Soil II.

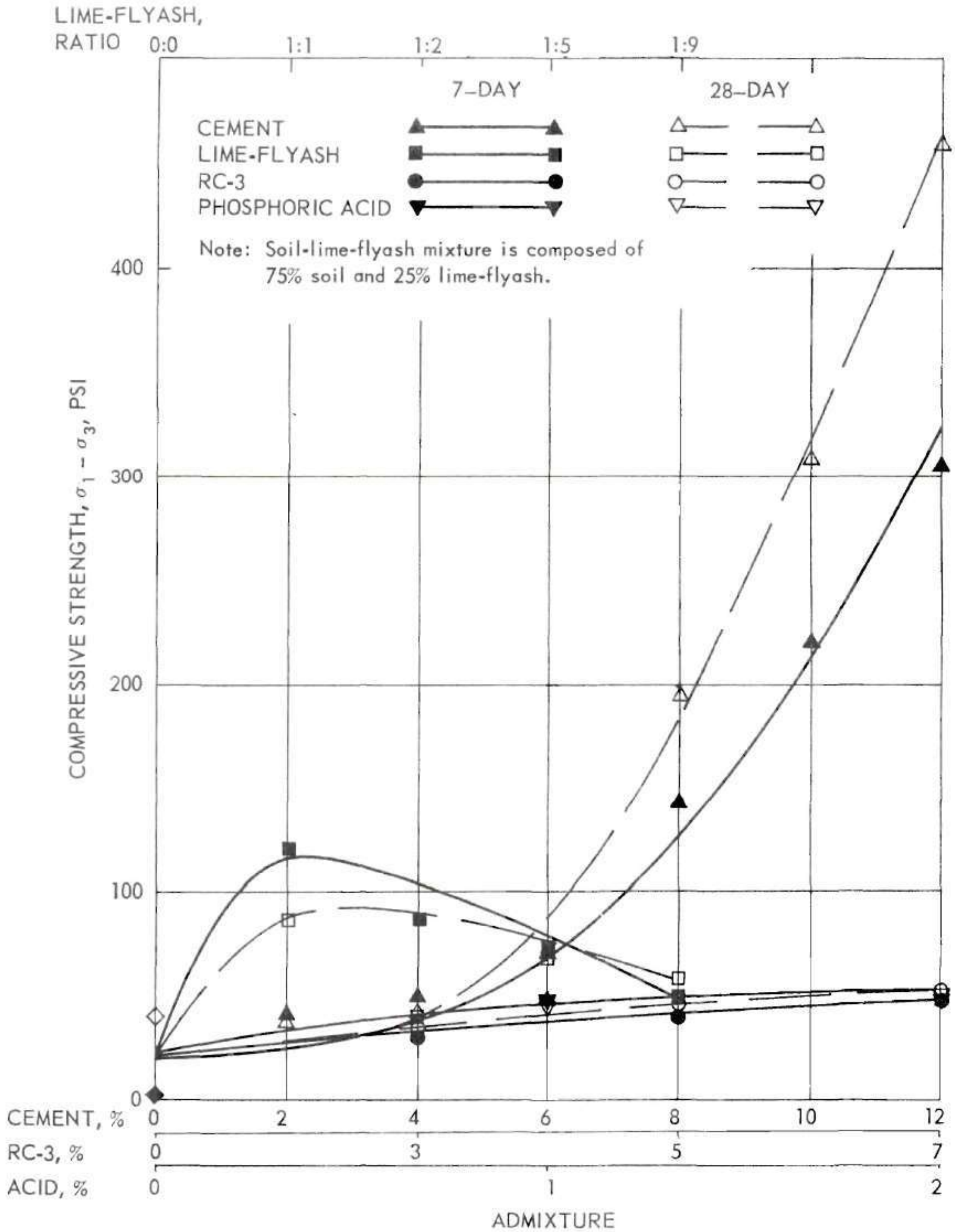

Figure 15. Relationship of Confined Compressive Strength and Admixture for Soil III.

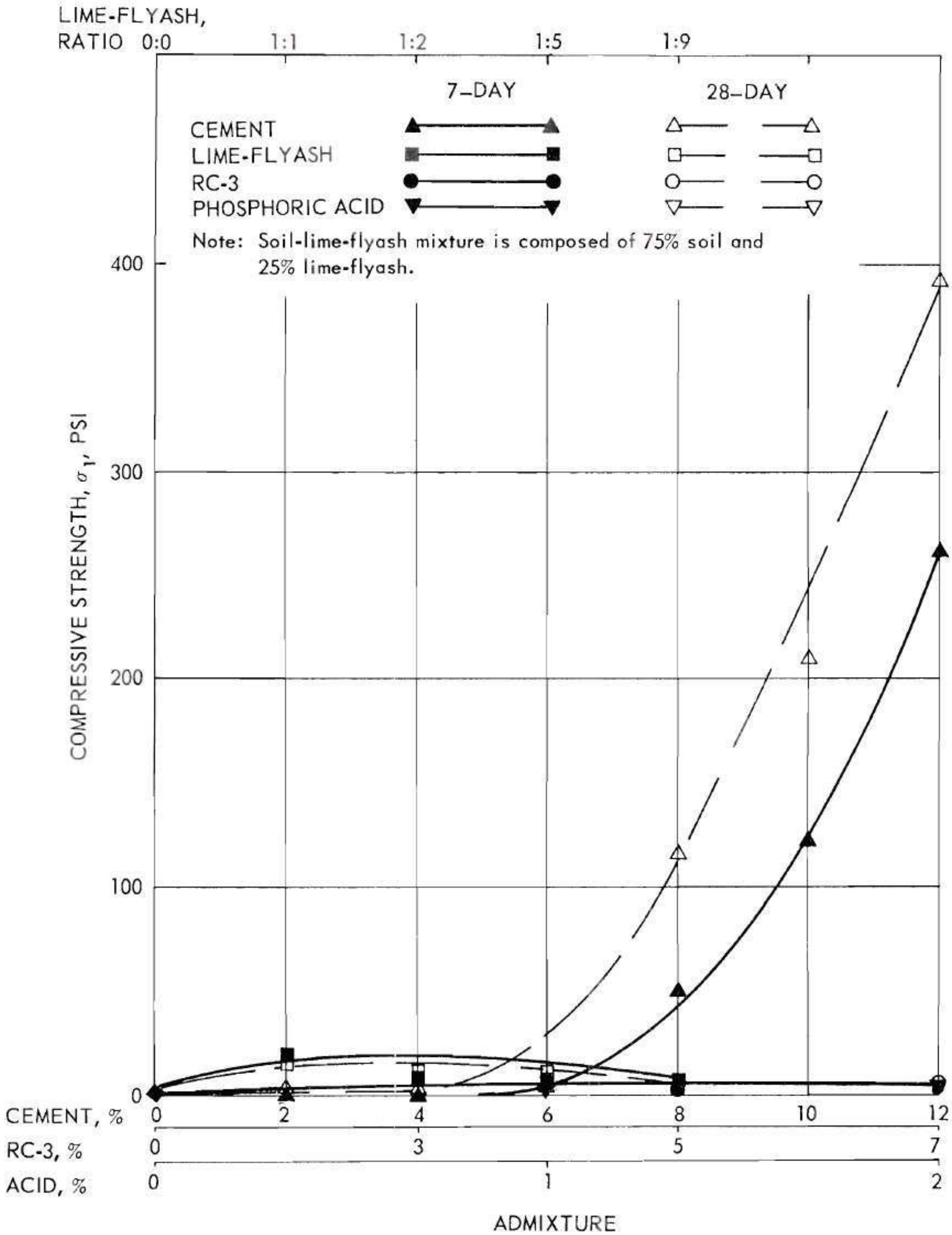

Figure 16. Relationship of Unconfined Compressive Strength and Admixture for Soil III.

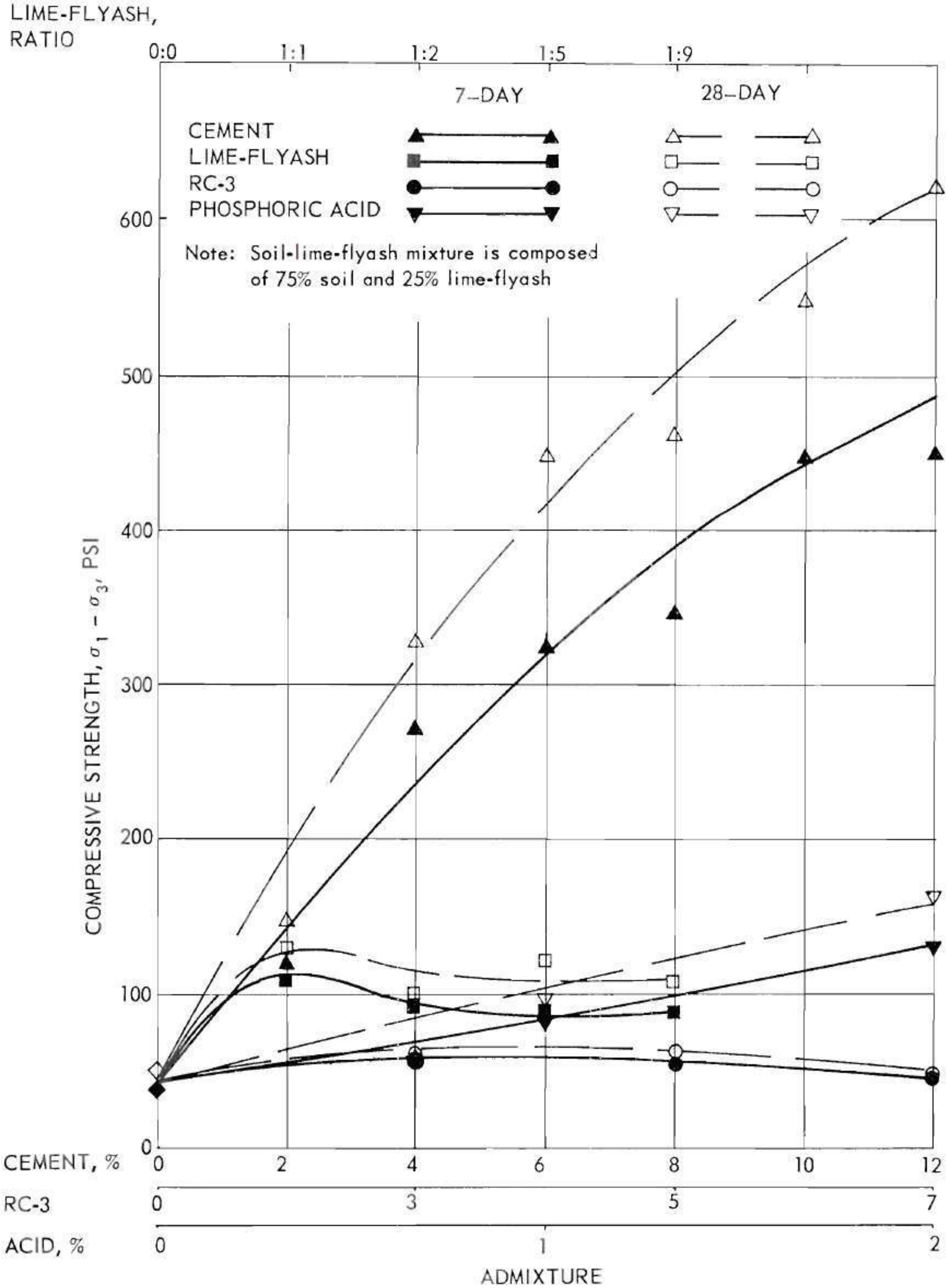

Figure 17. Relationship of Confined Compressive Strength and Admixture for Soil IV.

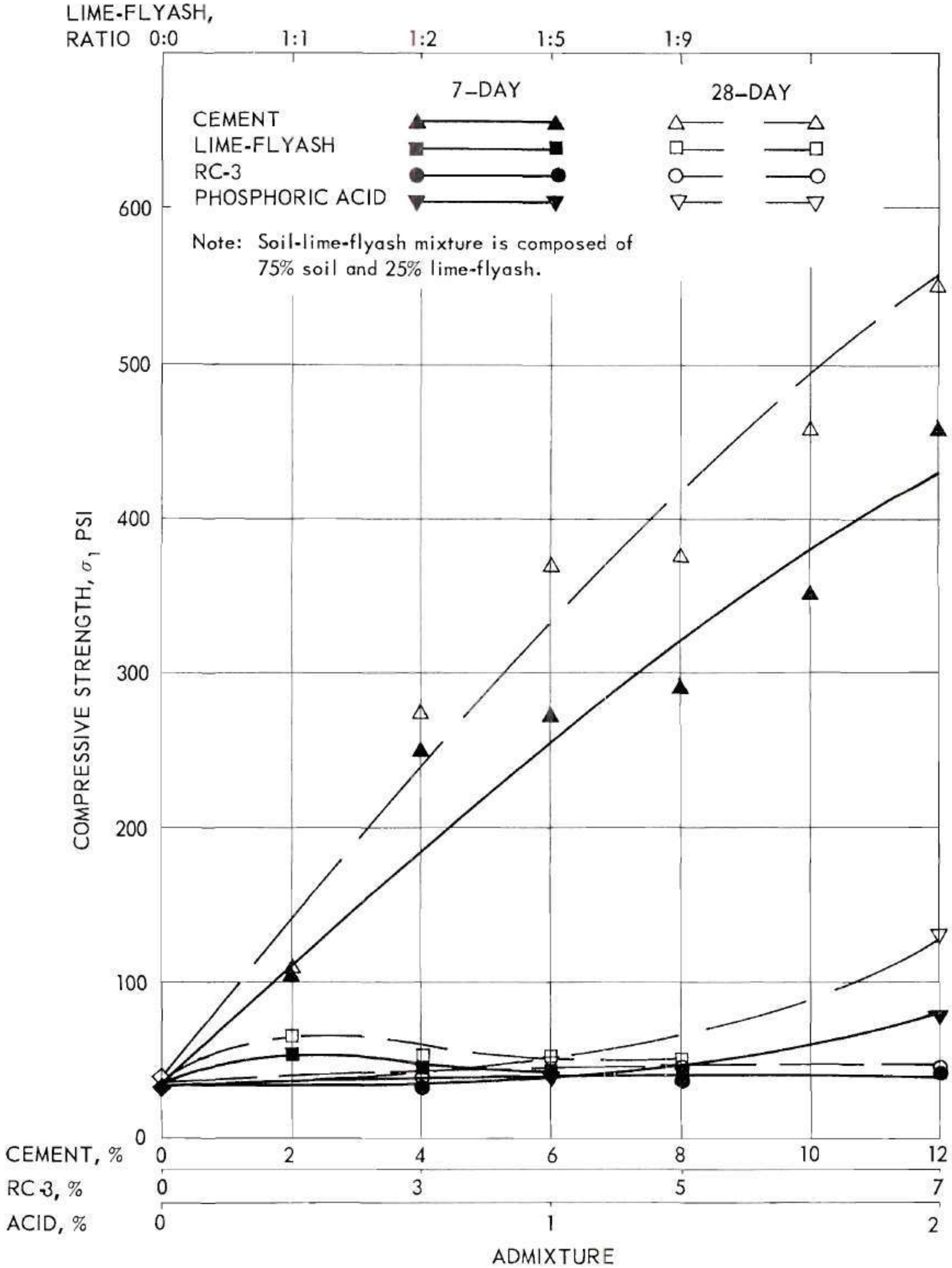

Figure 18. Relationship of Unconfined Compressive Strength and Admixture for Soil IV.

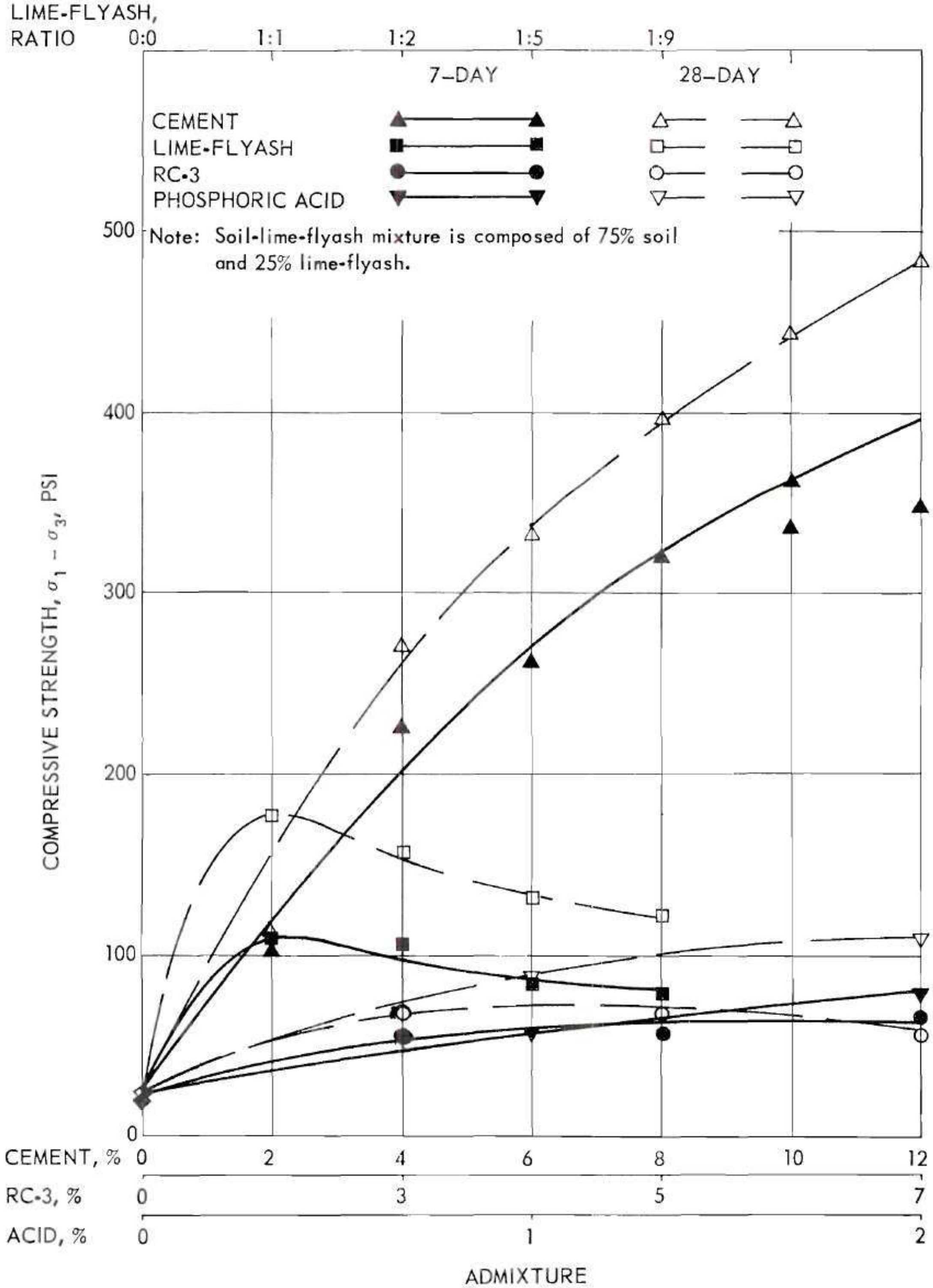

Figure 19. Relationship of Confined Compressive Strength and Admixture for Soil V.

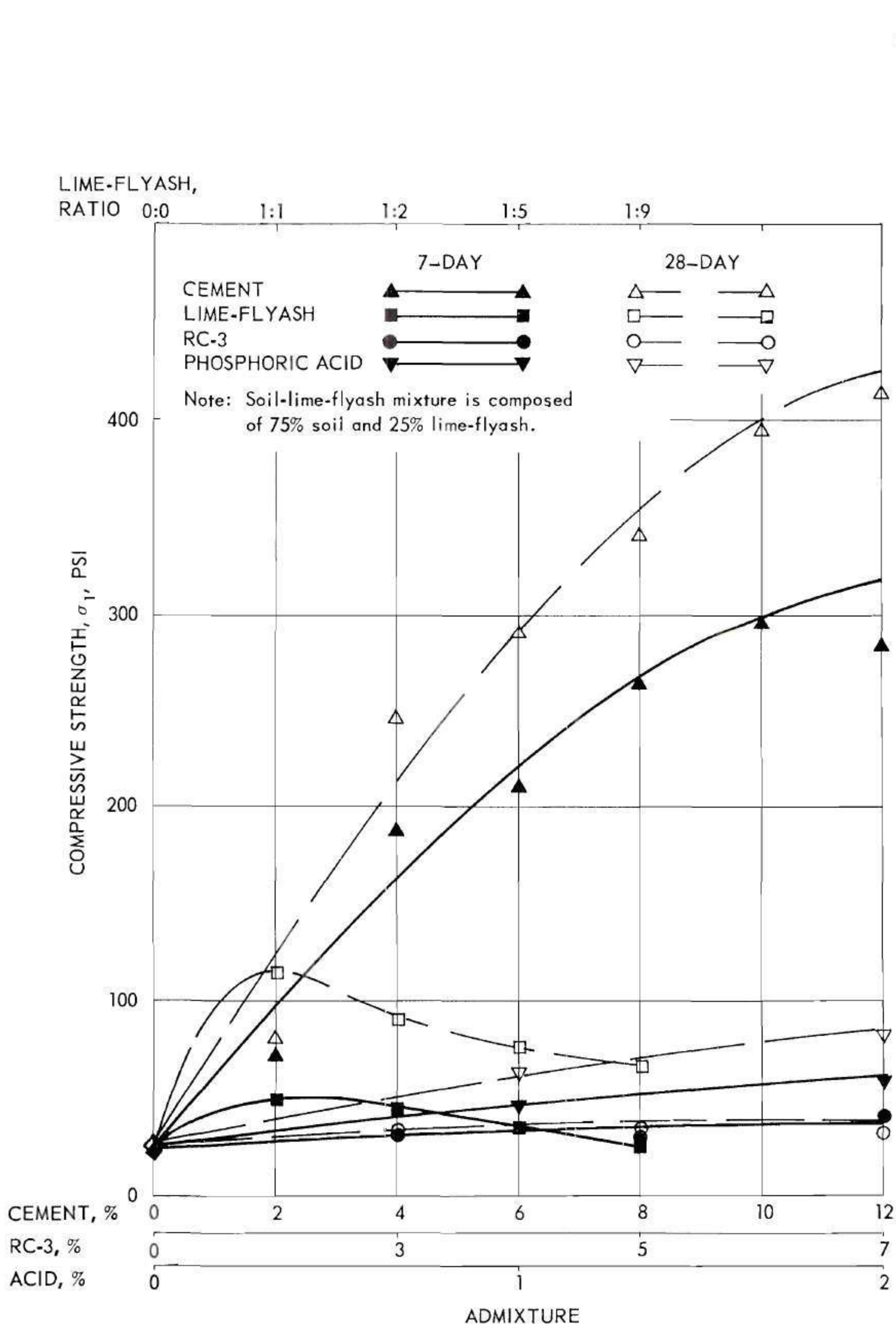

Figure 20. Relationship of Unconfined Compressive Strength and Admixture for Soil V.

higher percentages. The triaxial test curves and unconfined test curves had approximately the same shape with the triaxial test curves showing greater improvement at the lower percentages of cement. The 28 day test curves showed approximately a constant increase in strength over the 7 day test curves from 6 per cent to 12 per cent cement. The lime-flyash mixture gave an improved strength with little variation with the change in ratio of lime to flyash except at the 1:9 ratio which had a drop in strength to slightly higher than the soil with no admixture. Maximum strength obtained with this admixture compared with approximately 3 to 4 per cent portland cement. Strength gain with phosphoric acid was about double the raw soil strength but the maximum strength was only approximately 100 and 50 psi for the confined and unconfined tests, respectively. The addition of RC-3 caused only a slight increase in strength and was the poorest admixture from a strength standpoint.

The variation in strength with the addition of admixtures to Soil II is shown in Figures 13 and 14 and tabulated in Table 10. Portland cement was the most beneficial admixture with approximately a linear increase in strength with increasing percentages of cement. A strength of over 1000 psi was obtained with 12 per cent cement in both the triaxial and unconfined tests. There was greater increase in the 28 day strengths over the 7 day strength with increasing amounts of cement. The lime-flyash admixture caused an increase in strength with the maximum strength obtained with a 1:1 lime-flyash ratio. This maximum strength compared with the strength of approximately 3 per cent portland cement. A negligible increase in strength was obtained with phosphoric acid. The addition of RC-3 caused a decrease in strength with the greatest decrease at 3 per cent.

From Figures 15 and 16 and Table 11, it is noted that the addition of portland cement to Soil III had negligible effect on strength up to 6 per cent. The addition of more than 6 per cent greatly increased the strength with a rapid rise in the strength curves up through 12 per cent. The increase in strength of the 28 day tests also was greater at the higher cement contents. The lime-flyash mixture improved the strength of this soil with the 1:1 lime-flyash showing the greatest improvement. The strength increase caused by lime-flyash compared to approximately 7 per cent portland cement. The decrease in 28 day strength as compared to the 7 day strength may be attributed to the use of flyash from different plants for these tests. Phosphoric acid and RC-3 gave negligible increases in strength with this soil.

The addition of portland cement to Soil IV as shown in Figures 17 and 18 and Table 12 caused a marked increase in strength even with the 2 per cent addition. This increase in strength was approximately linear with the 28 day strength increasing over the 7 day strength at higher cement percentages. An increase in strength of approximately 300 per cent at 28 days was noted with the addition of 2 per cent phosphoric acid. This was approximately the same increase effected by 2 to 3 per cent portland cement. The addition of 1 per cent acid was less effective as was the 7 day curing period. The lime-flyash mixture was slightly effective at the 1:1 lime-flyash ratio with less strength gains at the higher flyash contents. Lime-flyash was more effective when tested in the triaxial test. RC-3 was not effective in increasing the strength of this soil, even reducing the strength with 7 per cent asphalt.

Figures 19 and 20 and Table 13 show the variation in strength with the various admixtures and Soil V. Portland cement was the most effective stabilizer with approximately 1000 per cent increase in strength at 12 per cent cement. The rate of increase was greatest up to 8 per cent. A steady increase in 28 day strength over the 7 day strength was noted with increasing amounts of cement. The lime-flyash mixture was also an effective stabilizer in this soil, especially after the 28 day curing period. Strengths approximately 4 times greater than the raw soil was effected by the addition of a 1:1 lime-flyash ratio with slightly less strength gains with the higher flyash content. A strength increase up to approximately 300 per cent was obtained with 2 per cent phosphoric acid with slightly less increase at 1 per cent. A negligible increase was obtained with RC-3 with little variation using the different percentages.

Cohesion and internal friction.--The load carrying ability of a soil is determined by its "cohesion" and/or "internal friction." In a sandy soil the mechanical interlocking of the solid particles provide the strength while in a cohesive soil, the mutual attraction between particles, which involves forces of electro-chemical nature, provide resistance to displacement. In most soils, the load carrying properties are derived from a combination of "cohesion" and "internal friction." These two parameters may be easily determined from plotting graphically the results of triaxial tests. This graphical plot is called a Mohr's diagram. Points which represent σ_1 and σ_3, compressive normal stresses and confining stresses respectively, are plotted along the abscissa and joined by a circle whose center is also on the abscissa. Circles are drawn corresponding to various confining pressures and a tangent is drawn to the circles. The intercept of this tangent with the y-axis is called "cohesion" and the slope of the tangent in degrees is the angle of "internal friction."

Data from the Mohr's diagram is tabulated in Table 14 and the variation in cohesion and angle of internal friction versus per cent portland cement is shown in Figures 21 through 25. Tests were made with the five soils combined with 0, 6, 9, 12 and 15 per cent portland cement using confining pressures of 0, 20 and 50 psi. Individual Mohr's diagrams for each per cent cement are shown in the appendix in Figures 26 through 50.

The addition of portland cement caused an increase in cohesion and angle of internal friction in all soils tested. Soil I, which had a cohesion of 2 psi, and angle of internal friction of 33 degrees with no admixture, had an increase in angle of internal friction at 6 per cent cement to approximately 50 degrees and remained constant with increasing amounts of cement. The cohesion in this soil increased rapidly up to about 9 per cent cement where the rate of increase decreased but with an increase through 15 per cent cement.

The angle of internal friction of Soil II was 29° with no admixture and increased to approximately 45° at 6 per cent cement where it remained approximately constant with increasing amounts of cement. Cohesion in this soil with no admixture was 5 psi and a marked increase was noted up to 12 per cent cement where the rate of increase lessened and at 15 per cent cement a cohesion of 275 psi was obtained.

Soil III, a fine uniformly graded sand, had no cohesion and an angle of internal friction of 29° with no admixture. The addition of

Table 14. Mohr's Diagram Data

Soil No.	Cement Content	Compressive Strength			Cohesion, C	Angle of Internal friction, ø
	%	psi			psi	degrees
		0*	20	50		
I	0	7	81	179	2	33
	6	148	261	574	30	49
	9	564	774	862	110	49
	12	712	883	1113	130	51
	15	750	1043	1080	145	49
II	0	13	84	158	5	29
	6	354	488	702	70	48
	9	751	873	1004	162	43
	12	1035	1114	1271	239	41
	15	1310	1448	1589	275	45
III	0	0	59	142	0	29
	6	5	68	165	2	34
	9	210	305	413	52	38
	12	389	484	772	88	41
	15	793	884	1054	180	41
IV	0	38	59	86	19	0
	6	369	465	564	95	36
	9	415	466	569	120	30
	12	550	640	836	136	40
	15	647	744	862	153	39
V	0	25	45	73	12	0
	6	291	352	440	83	31
	9	403	492	551	115	31
	12	413	504	585	123	31
	15	454	608	672	136	31

*Note: The 0, 20, and 50 indicate confining pressure in psi in the triaxial test.

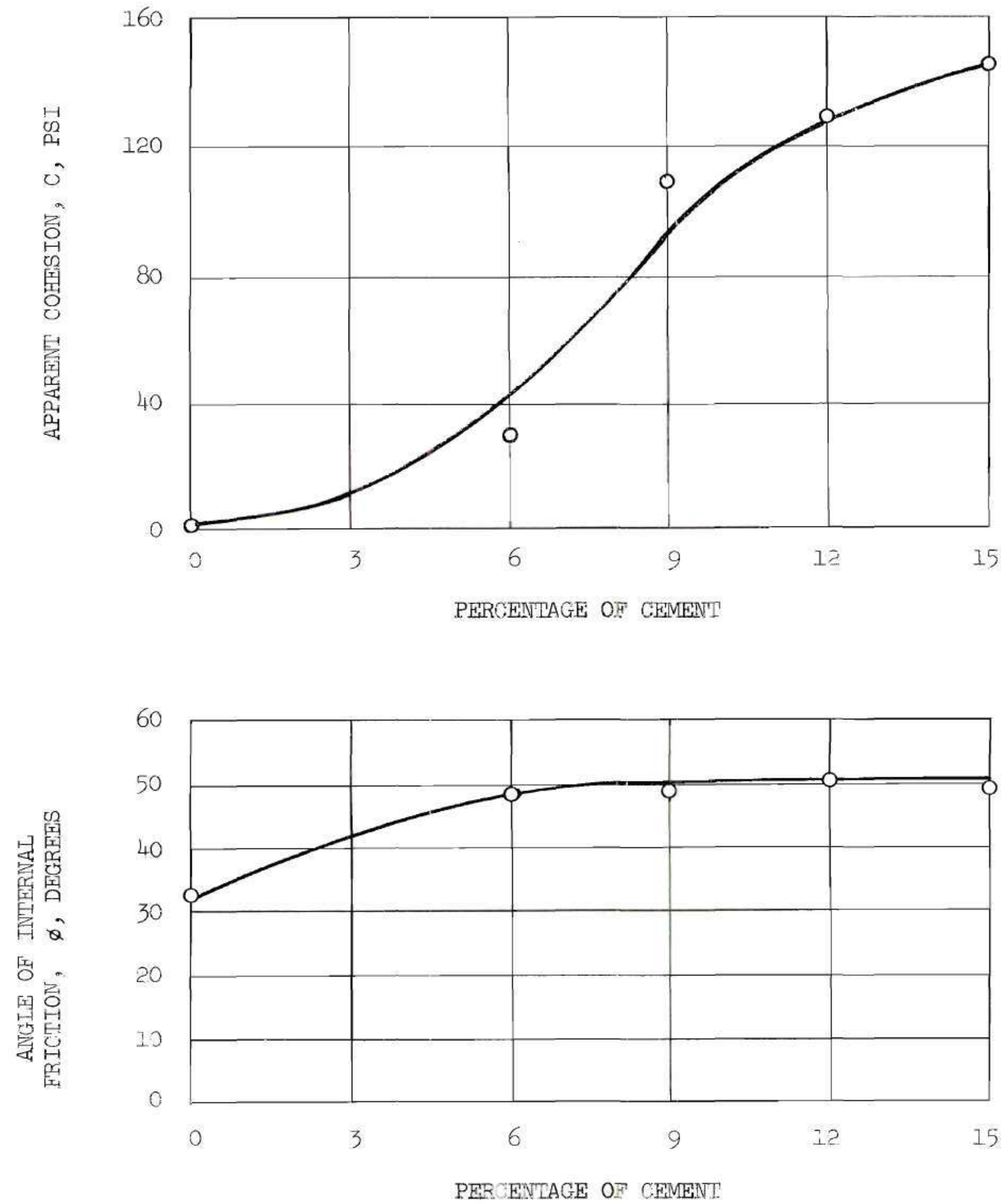

Figure 21. Apparent Cohesion and Angle of Internal Friction Versus Cement Content for Soil I.

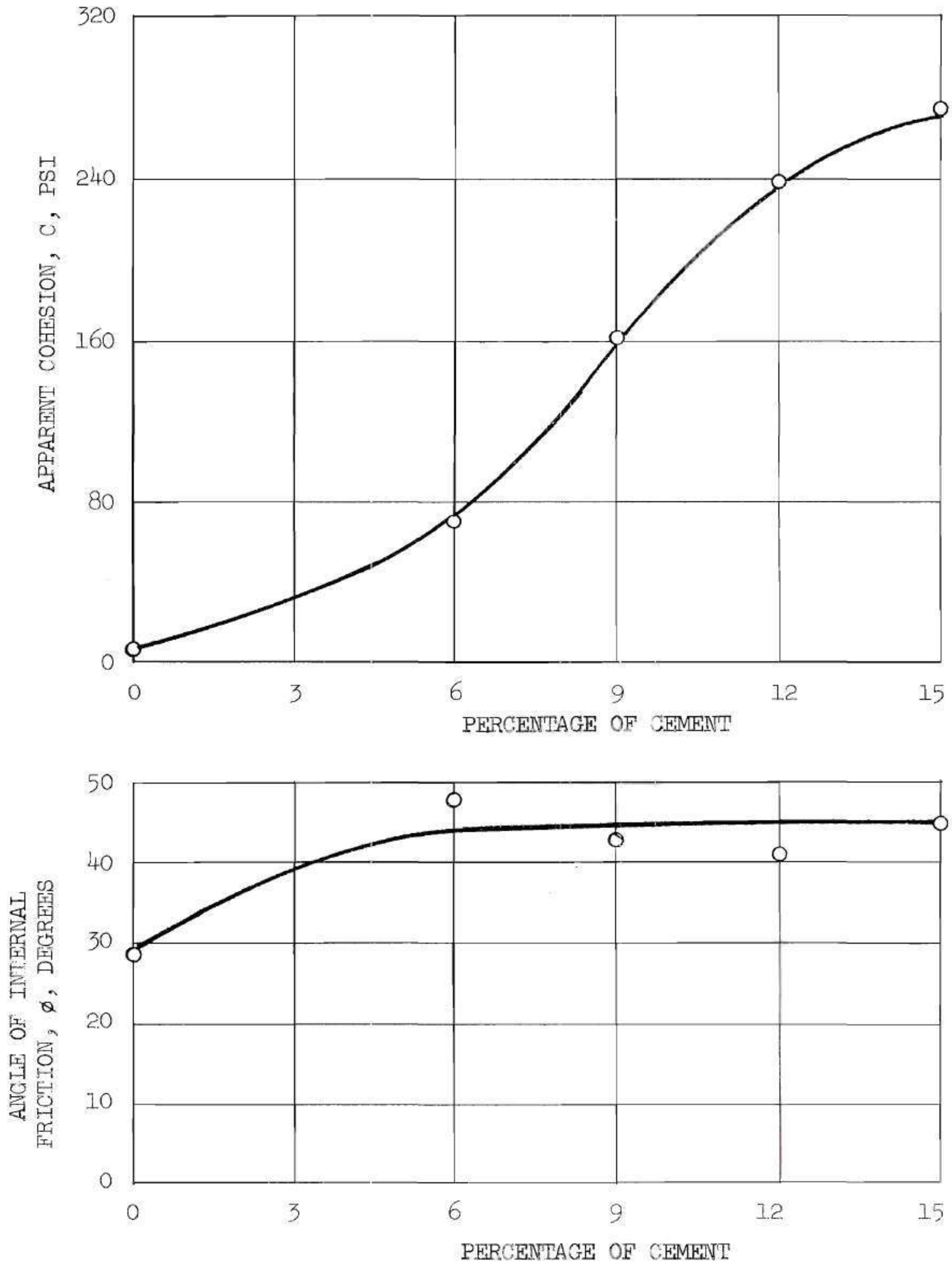

Figure 22. Apparent Cohesion and Angle of Internal Friction Versus Cement Content for Soil II.

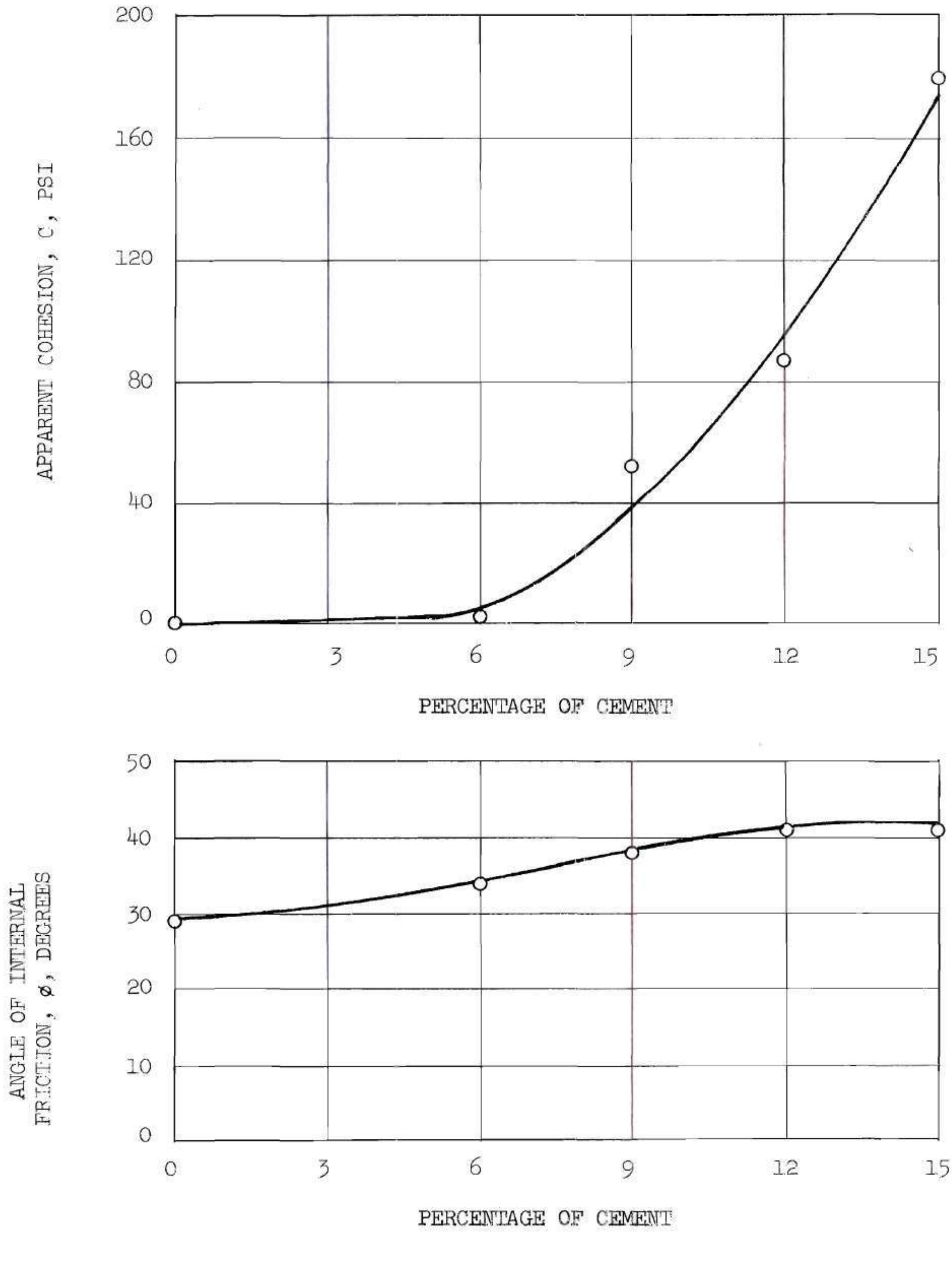

Figure 23. Apparent Cohesion and Angle of Internal Friction Versus Cement Content for Soil III.

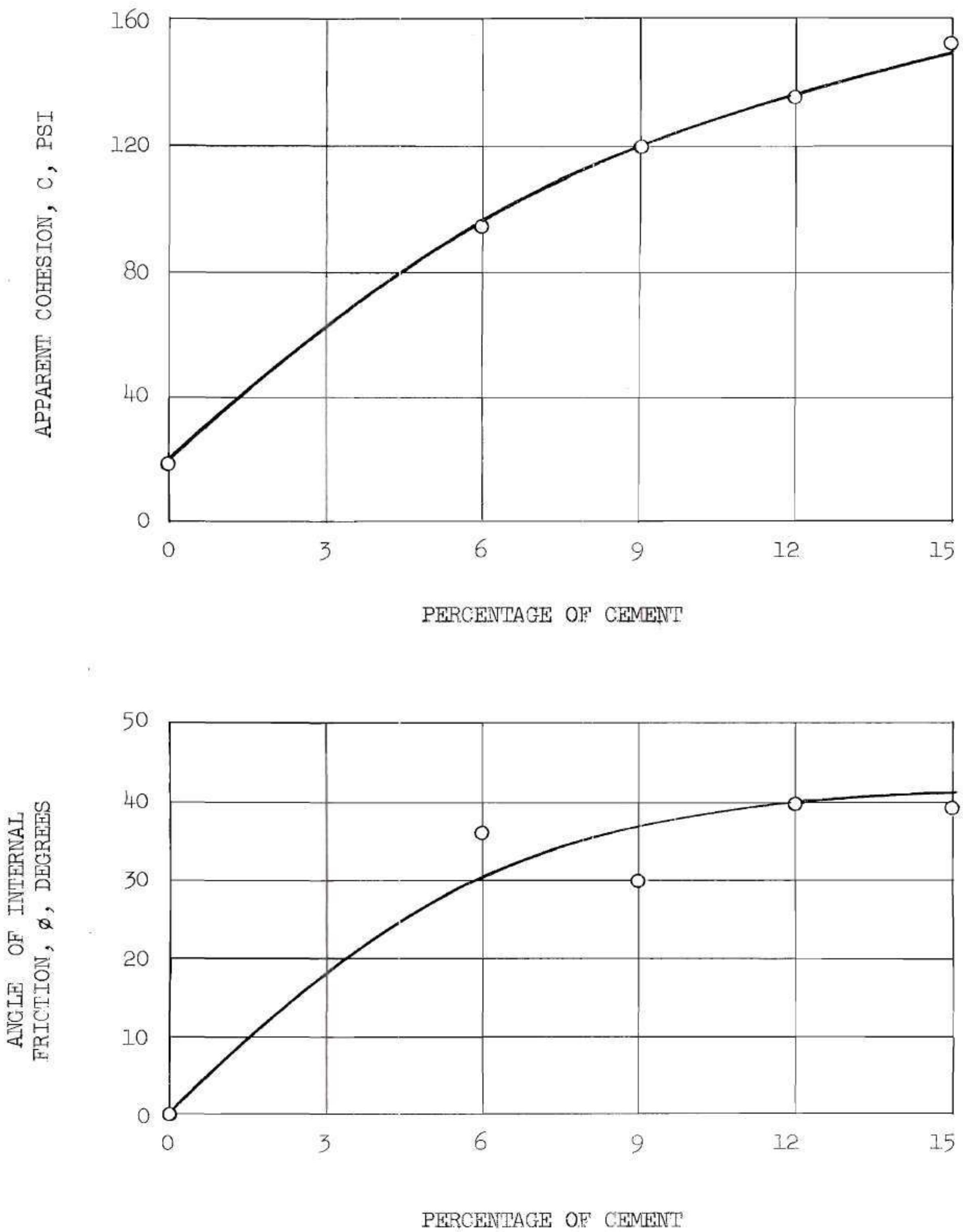

Figure 24. Apparent Cohesion and Angle of Internal Friction Versus Cement Content for Soil IV.

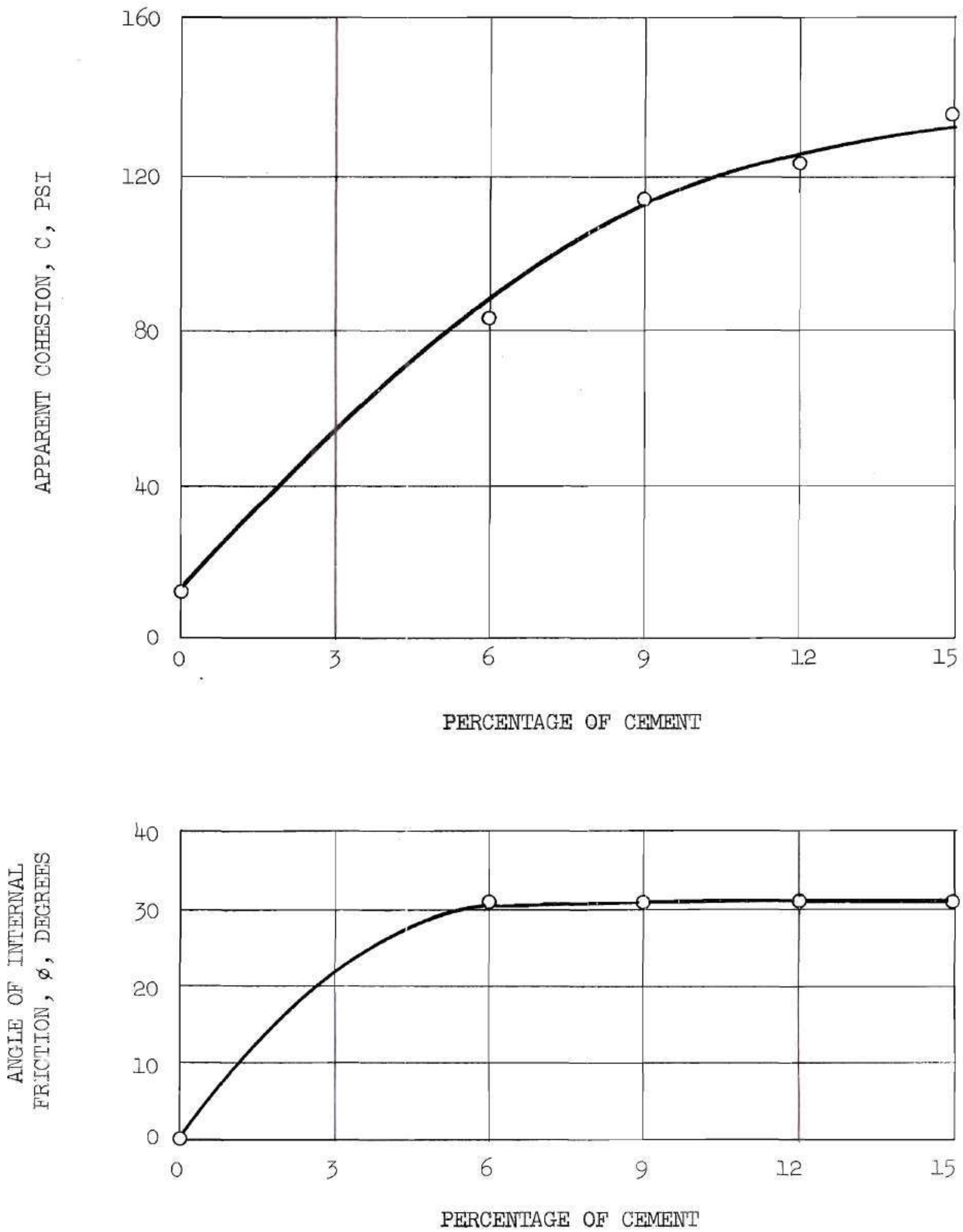

Figure 25. Apparent Cohesion and Angle of Internal Friction Versus Cement Content for Soil V.

cement caused an increase in angle of internal friction up to 41° at 12 per cent and remained the same for 15 per cent cement. There was little change in cohesion with 6 per cent cement but a rapid increase then up through 15 per cent cement where the cohesion was 180 psi.

Cohesion and angle of internal friction in Soil IV with no admixture were 19 psi and 0° respectively. The cohesion increased with increasing amounts of cement up to approximately 150 psi at 15 per cent. The angle of internal friction increased rapidly with approximately 30° at 6 per cent to a maximum of 40° at 12 and 15 per cent cement.

Soil V also had no internal friction with no admixture and a cohesion of 12 psi. The addition of cement caused an increase to 31° at 6 per cent and remained constant at that figure with increasing amounts of cement. Cohesion increased rapidly up through 9 per cent cement to 115 psi, then with a lesser rate of increase up to 136 psi at 15 per cent.

CHAPTER V

CONCLUSIONS

The following conclusions have been reached as a result of this study:

1. The addition of admixtures effects the maximum dry density and optimum moisture of a soil.
2. Strength of various soils can be improved by the addition of certain admixtures.
3. Portland cement effected the greatest increase in strength in all soils tested.
   a. Compressive strength increased with increased amounts of cement.
   b. The greatest rate of increase, in general, is at the higher cement contents.
   c. Increased strength varies directly with increased curing time.
4. The angle of internal friction, ø, and cohesion, c, is increased by the addition of portland cement.
5. The addition of 25% lime-flyash to a soil improved the strength of all soils.
   a. A 1:1 lime-flyash ratio gave the greatest strength improvement except with one soil where little change was noted from a 1:1 to 1:5 ratio.

b. Lime-flyash soil mixtures increased in strength with increased curing time.

6. Phosphoric acid caused a nominal increase in strength of all soils.

   a. The greatest improvement with this admixture was in the finer grain soils with the higher clay content.

   b. Two per cent acid gave a greater strength increase than did 1% acid.

   c. Strength after curing for 28 days was higher than after 7 days curing.

7. The addition of RC-3 caused negligible strength increases and in some cases caused a reduction in strength.

CHAPTER VI

RECOMMENDATIONS

The following recommendations are made for further study:

1. Further testing of the susceptibility of various soils to stabilization with portland cement.
2. An evaluation of the effects of variation in density and moisture on stabilized soils.
3. A study of the effects of exposure of high moisture conditions to stabilized soils during and after curing.
4. A study of volume change in soil-cement.
5. A study of cement stabilized soil-aggregate mixtures.
6. A determination of design requirements for various types of roads.

A P P E N D I X

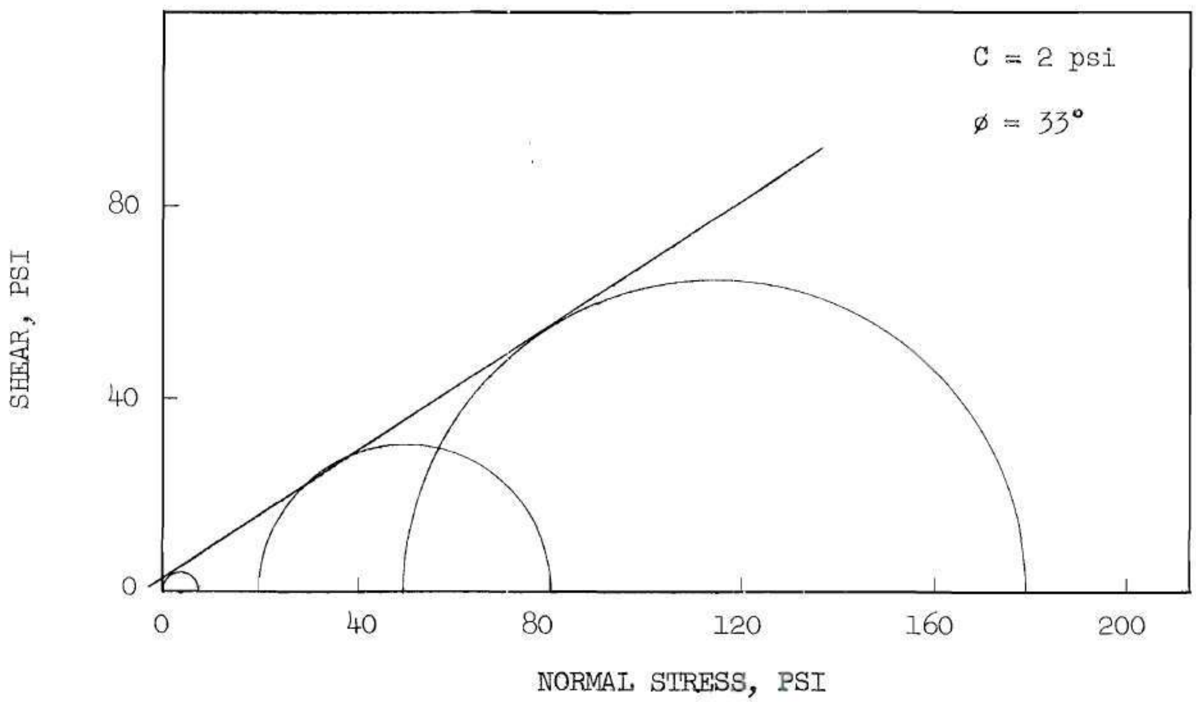

Figure 26. Mohr's Diagram for Soil I with no Admixture.

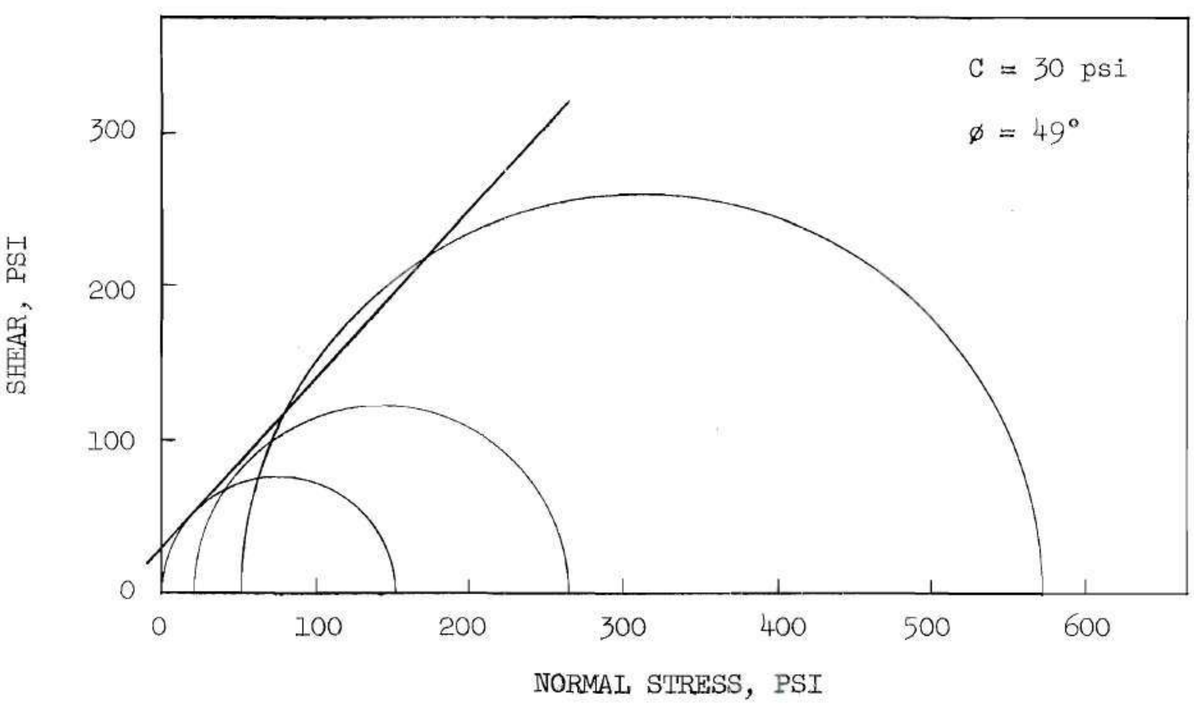

Figure 27. Mohr's Diagram for Soil I with 6% Portland Cement.

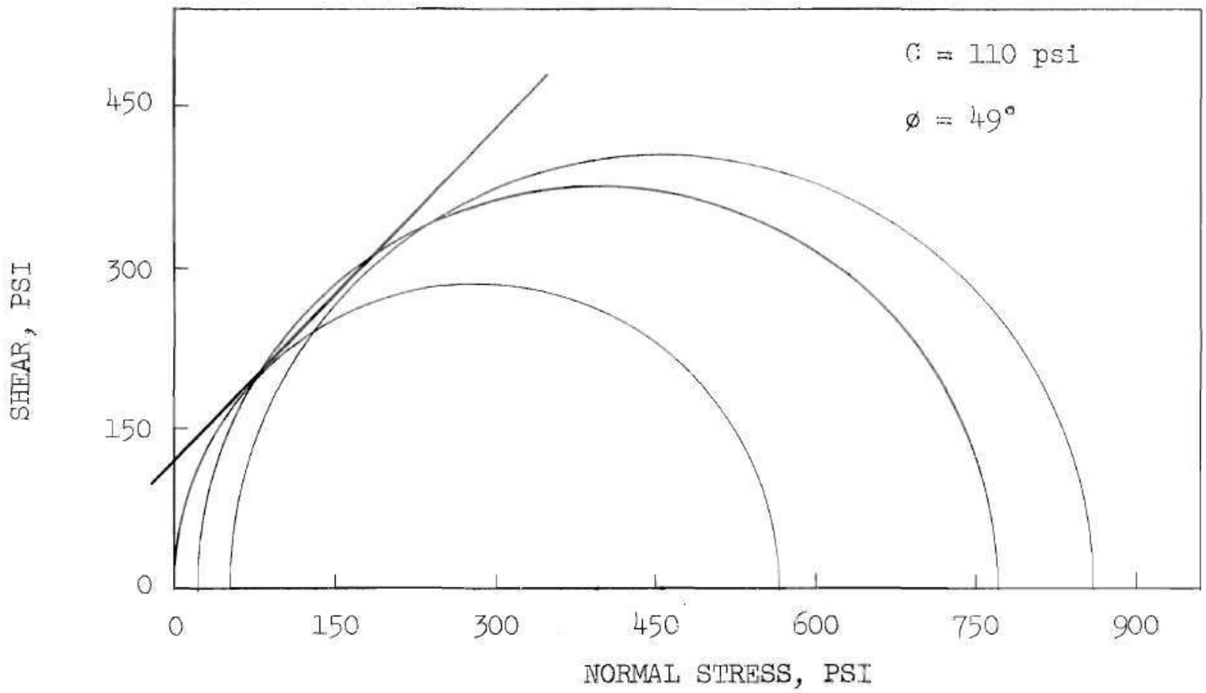

Figure 28. Mohr's Diagram for Soil I with 9% Portland Cement.

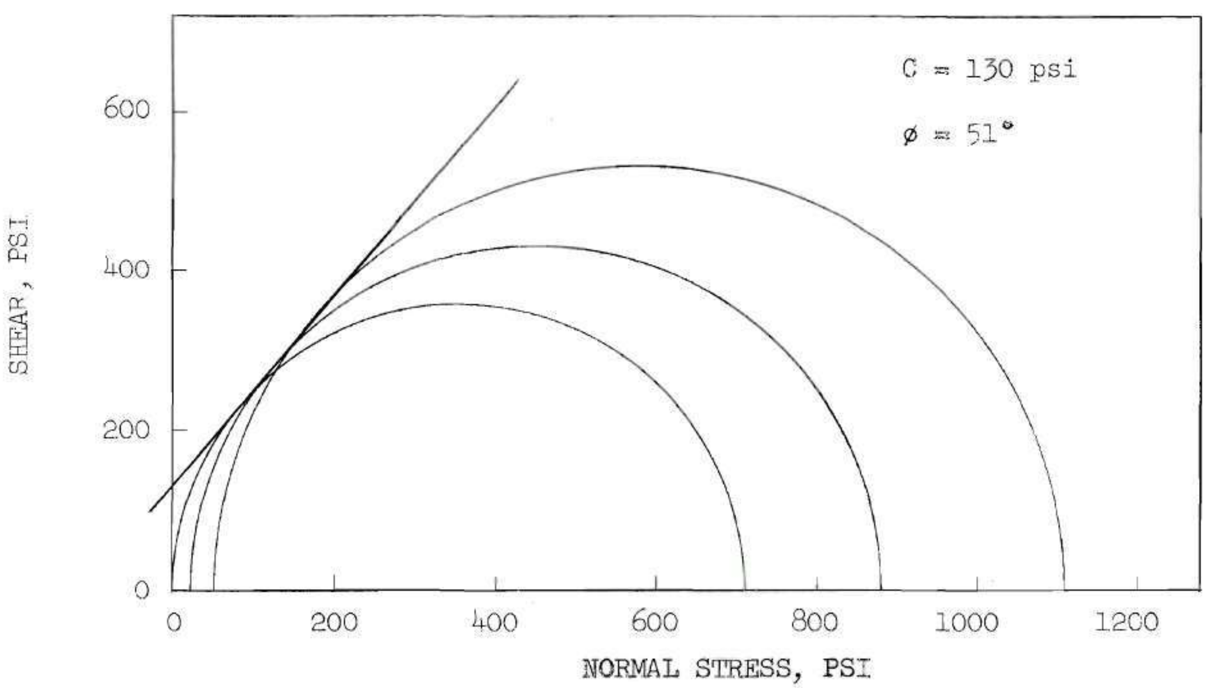

Figure 29. Mohr's Diagram for Soil I with 12% Portland Cement.

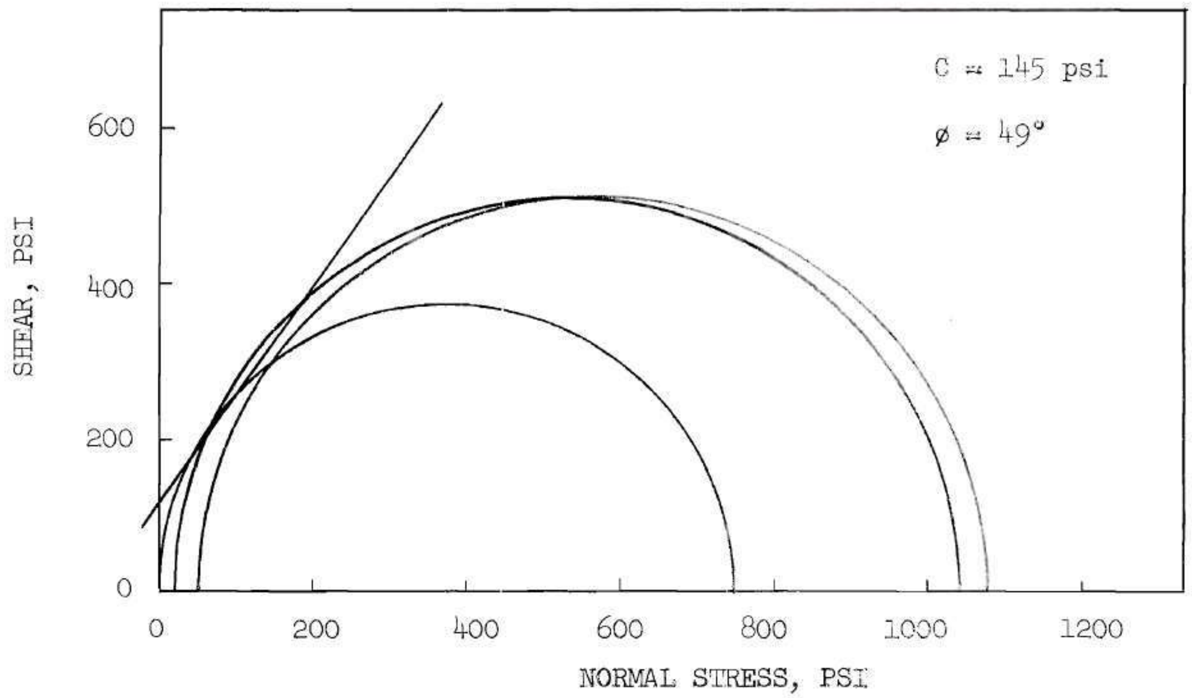

Figure 30. Mohr's Diagram for Soil I with 15% Portland Cement.

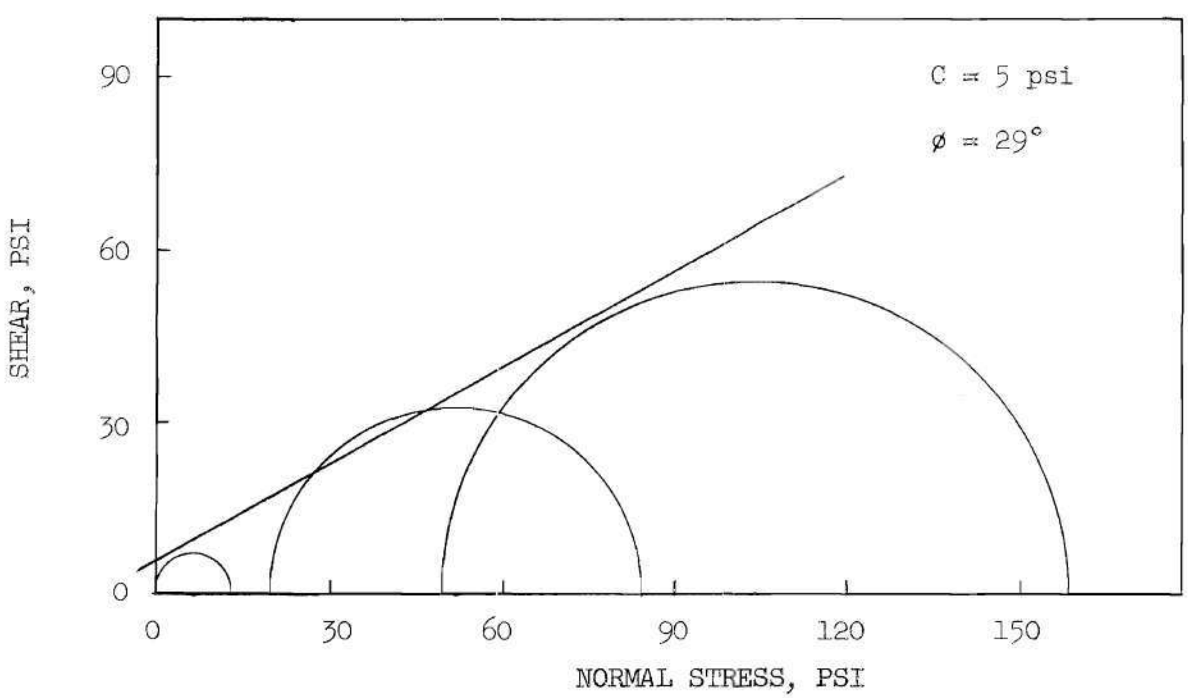

Figure 31. Mohr's Diagram for Soil II with no Admixture.

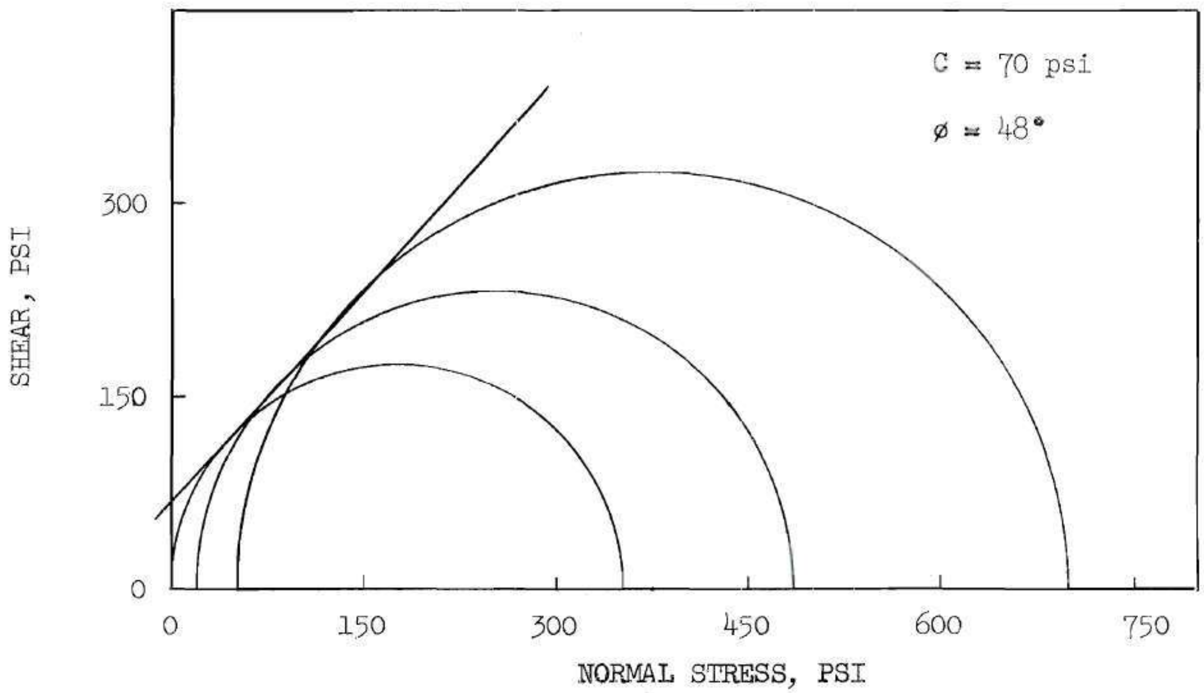

Figure 32. Mohr's Diagram for Soil II with 6% Portland Cement.

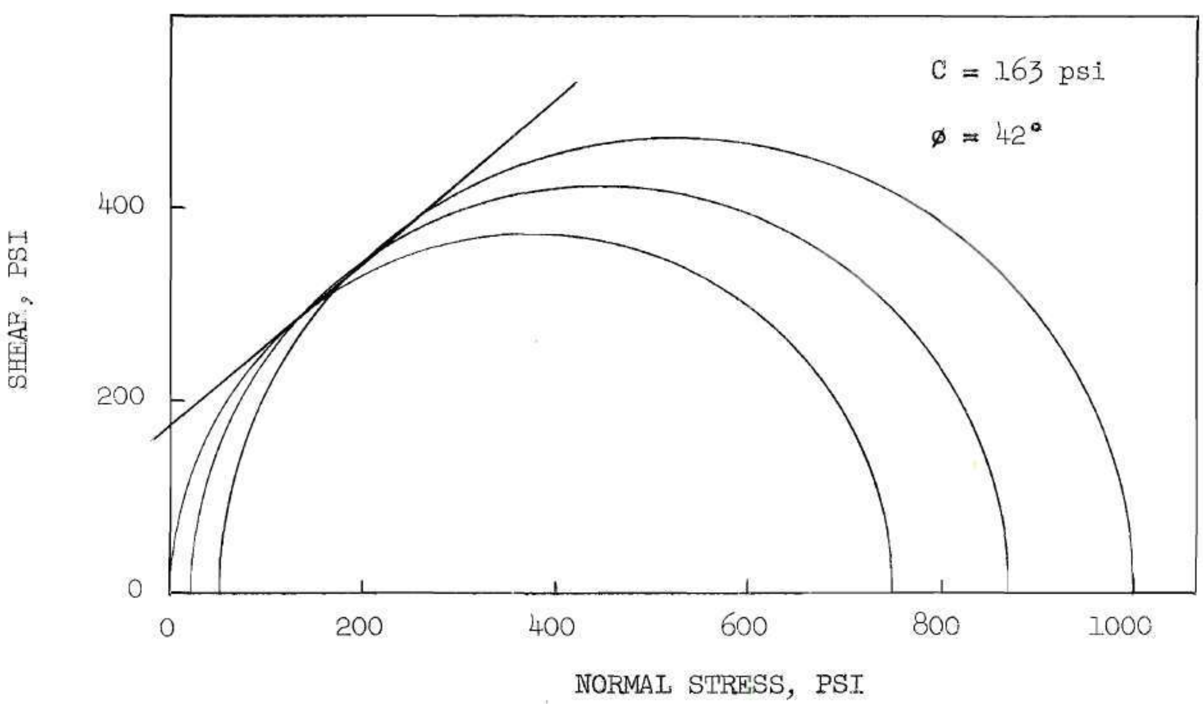

Figure 33. Mohr's Diagram for Soil II with 9% Portland Cement.

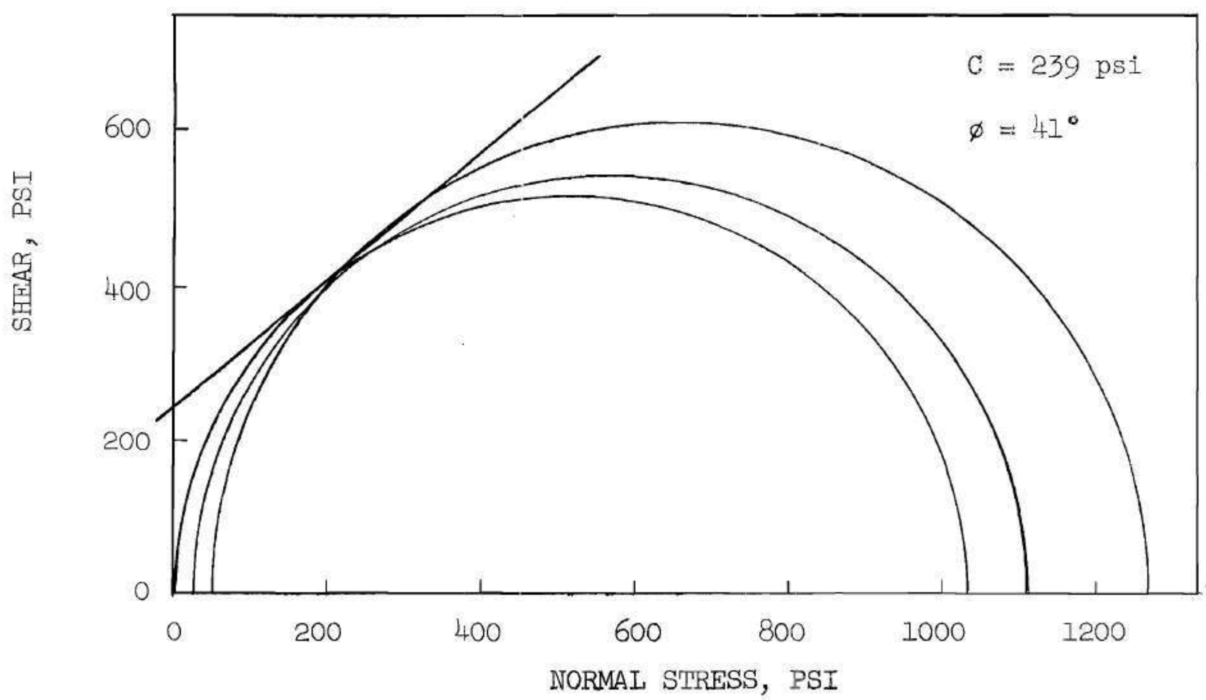

Figure 34. Mohr's Diagram for Soil II with 12% Portland Cement.

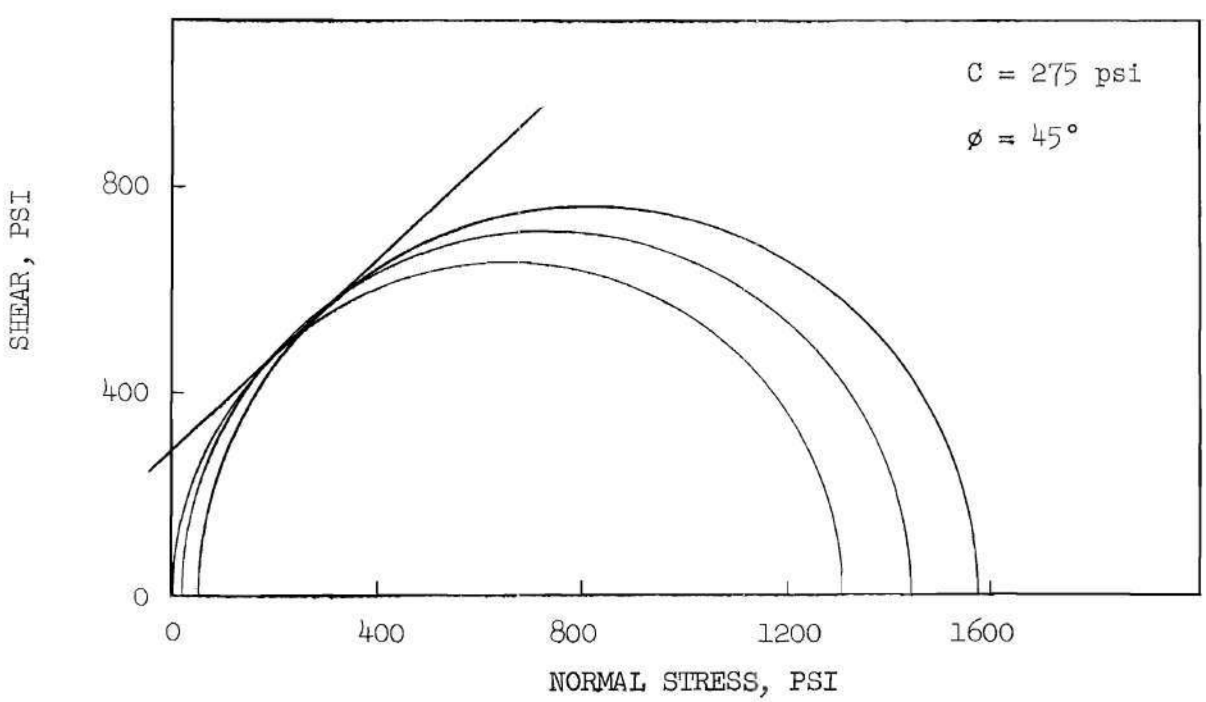

Figure 35. Mohr's Diagram for Soil II with 15% Portland Cement.

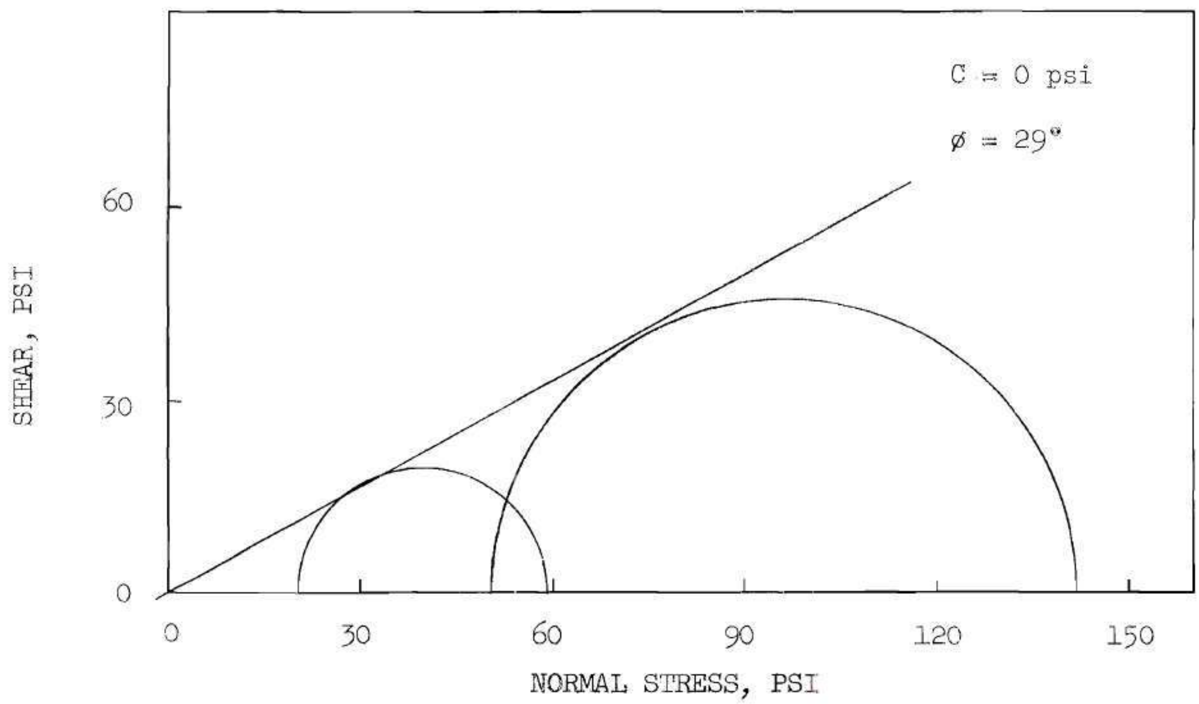

Figure 36. Mohr's Diagram for Soil III with no Admixture

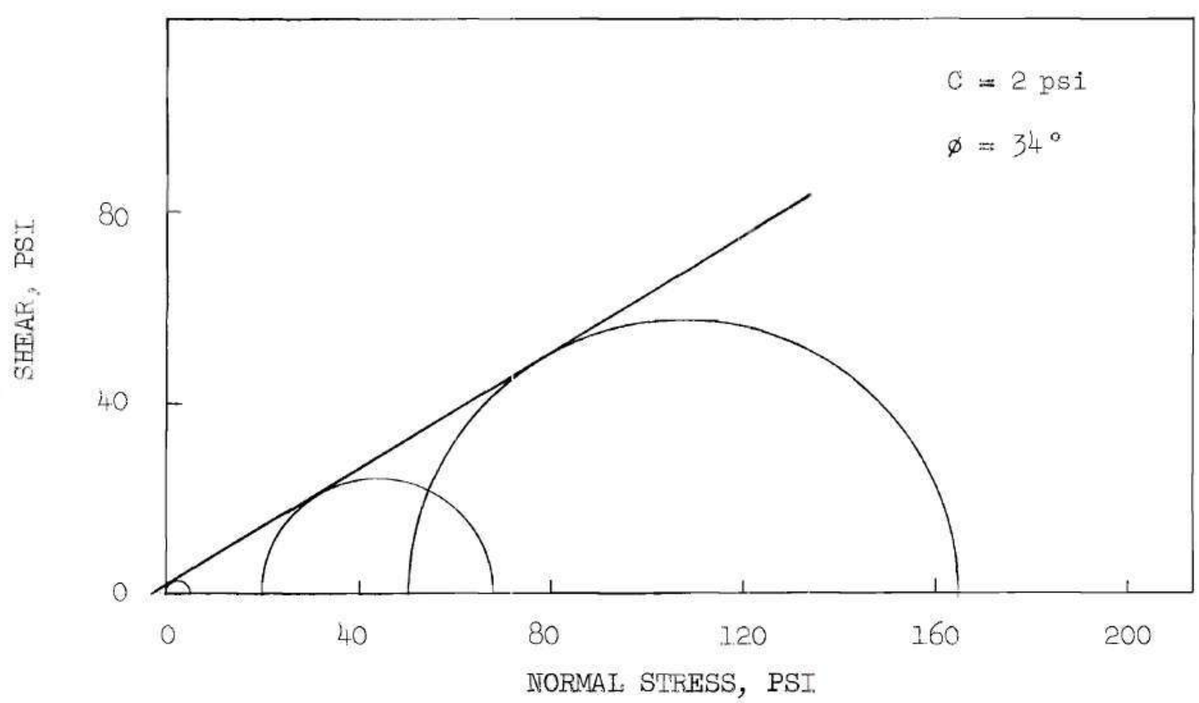

Figure 37. Mohr's Diagram for Soil III with 6% Portland Cement.

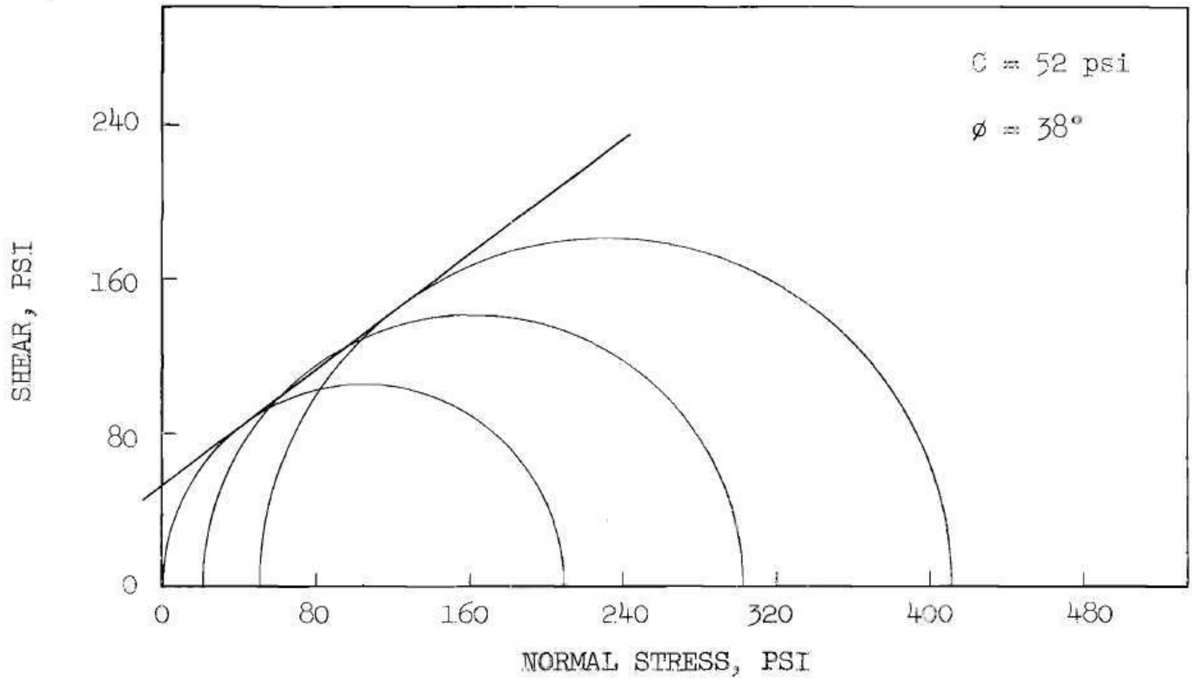

Figure 38. Mohr's Diagram for Soil III with 9% Portland Cement.

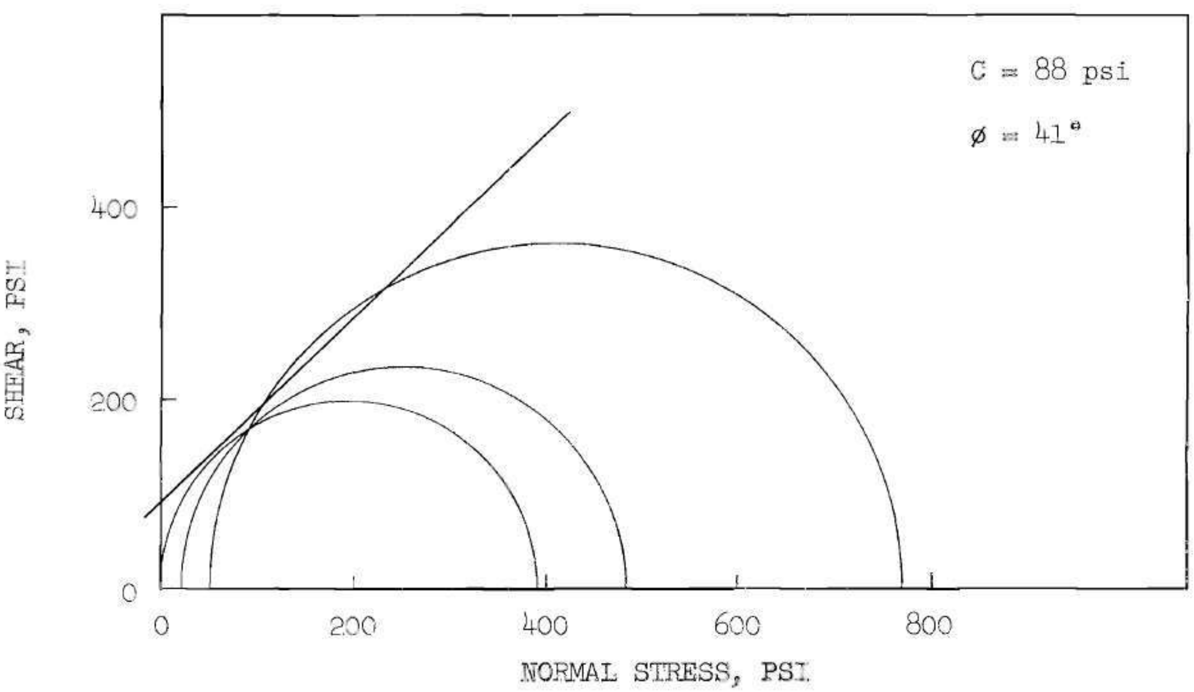

Figure 39. Mohr's Diagram for Soil III with 12% Portland Cement.

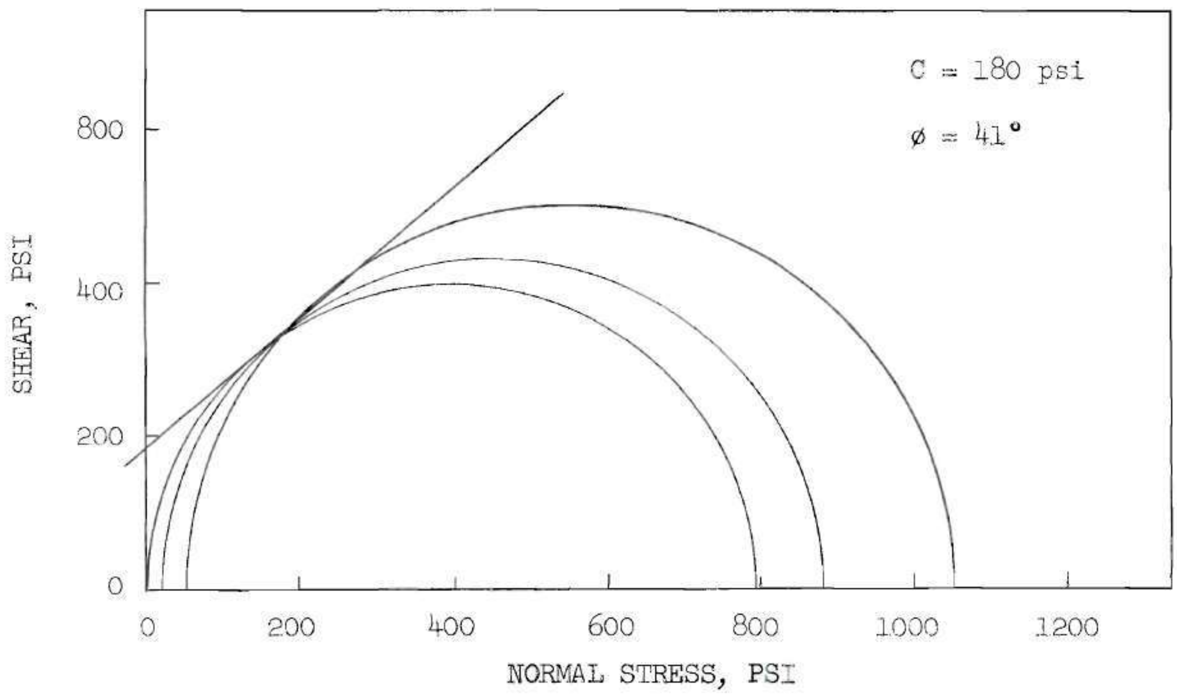

Figure 40. Mohr's Diagram for Soil III with 15% Portland Cement.

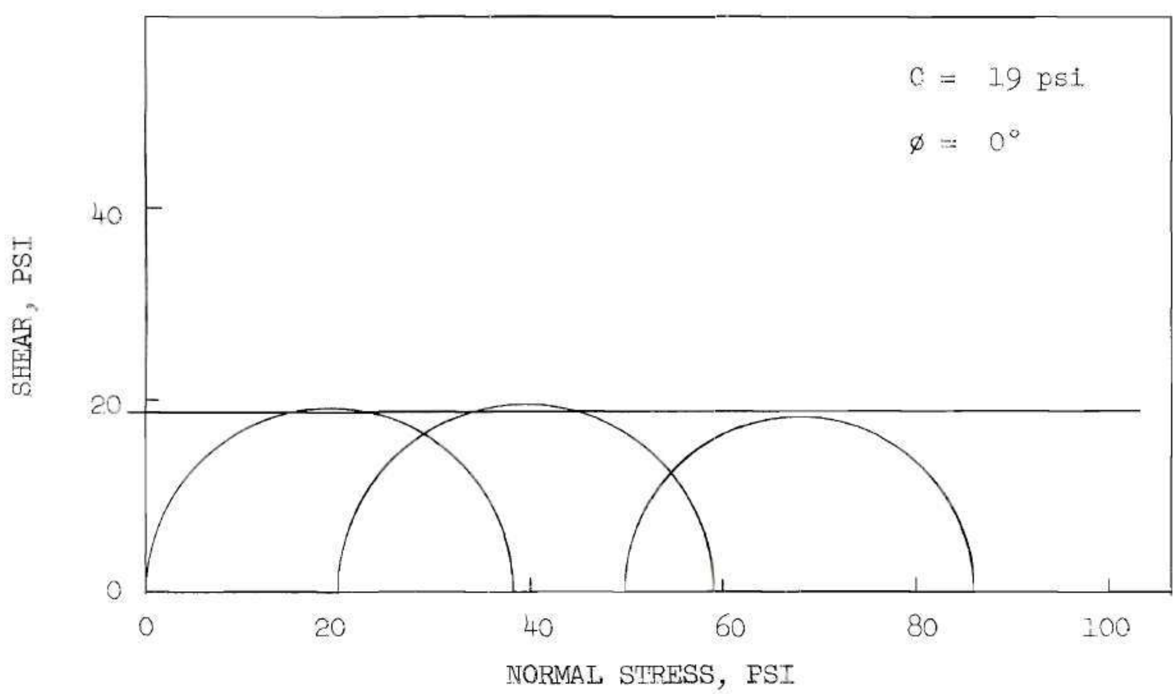

Figure 41. Mohr's Diagram for Soil IV with no Admixture.

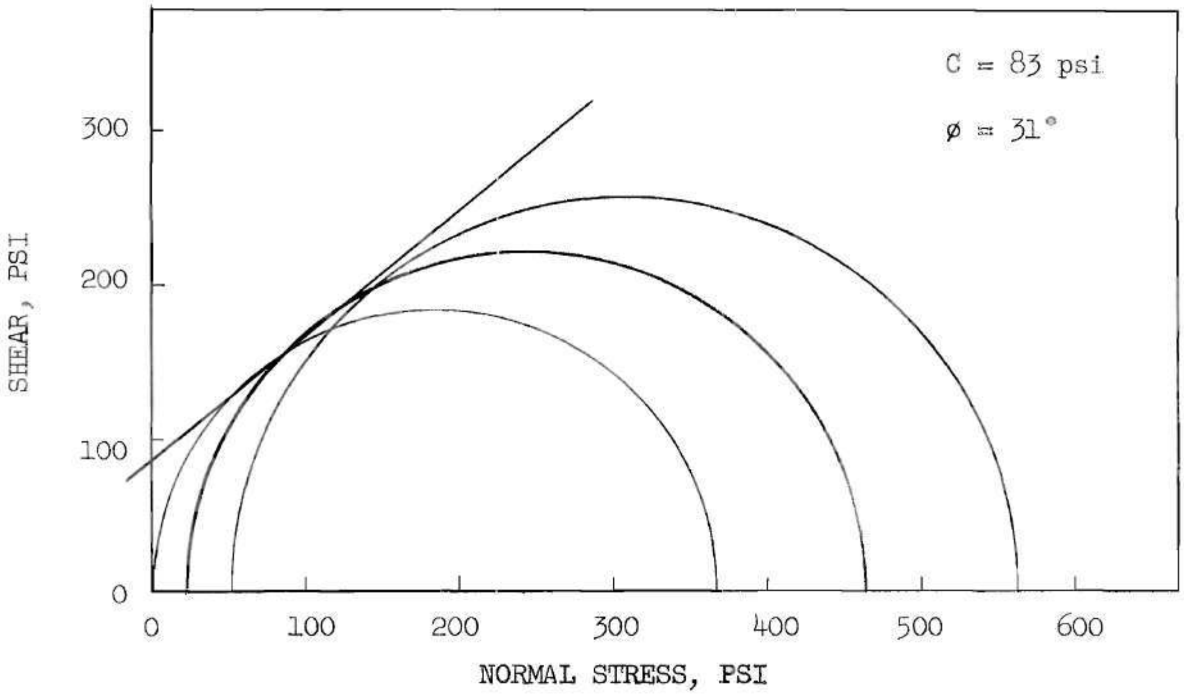

Figure 42. Mohr's Diagram for Soil IV with 6% Portland Cement.

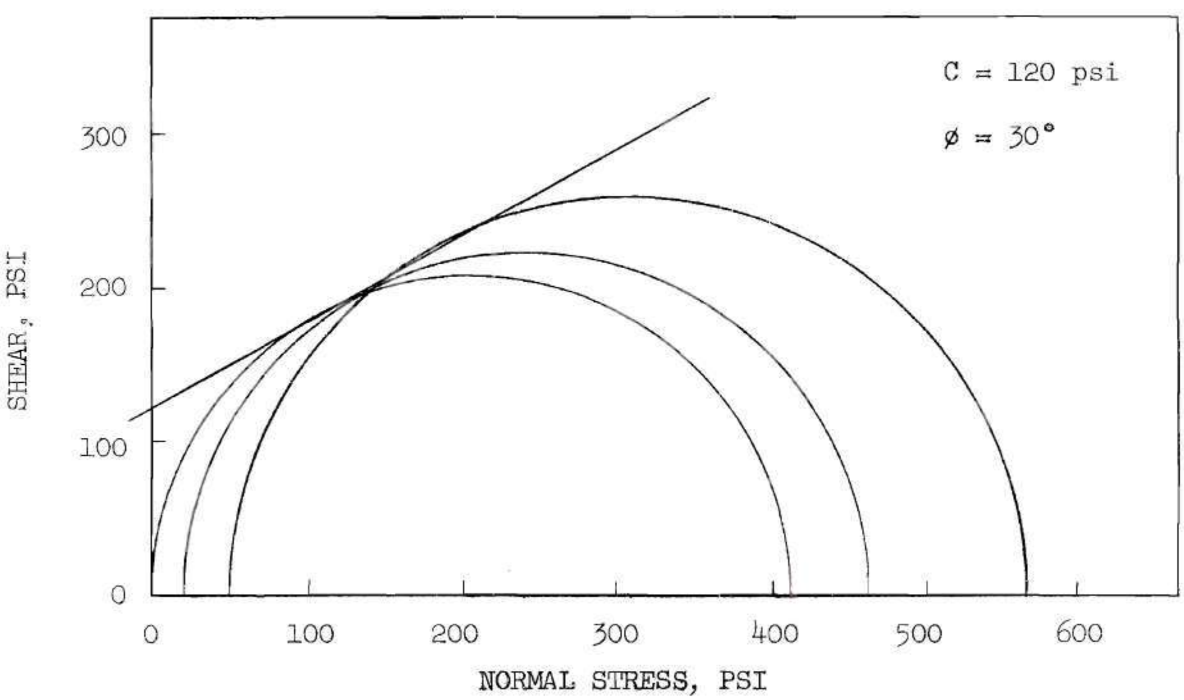

Figure 43. Mohr's Diagram for Soil IV with 9% Portland Cement.

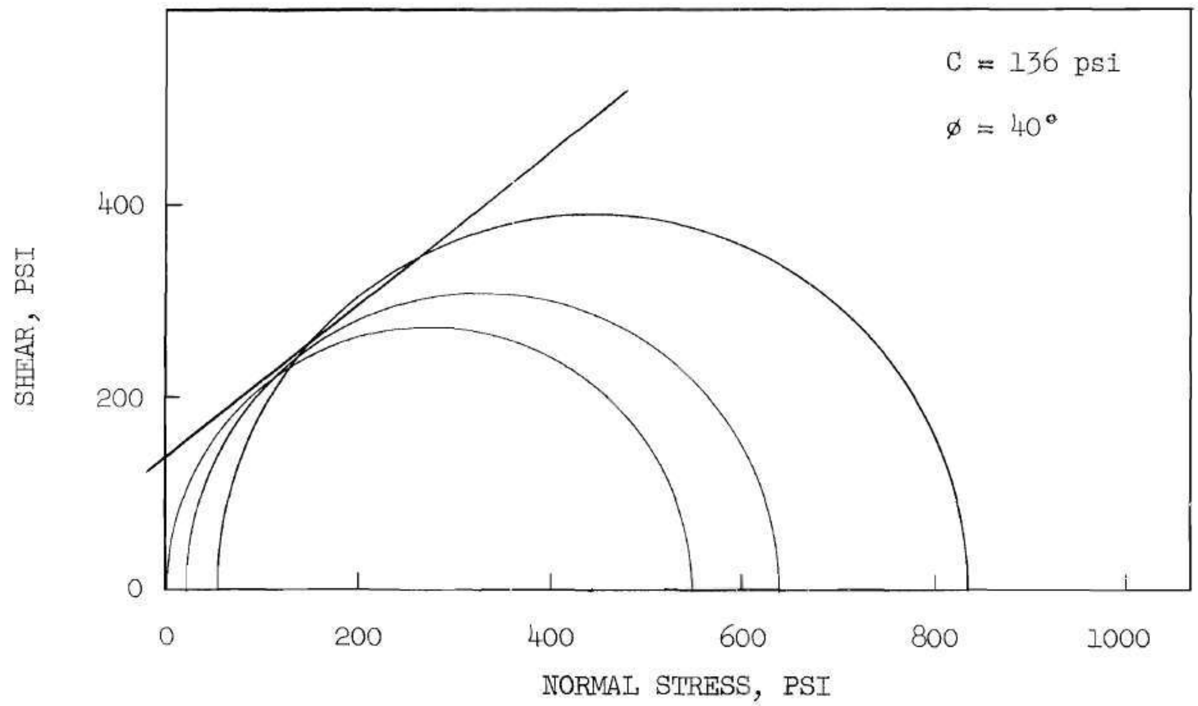

Figure 44. Mohr's Diagram for Soil IV with 12% Portland Cement.

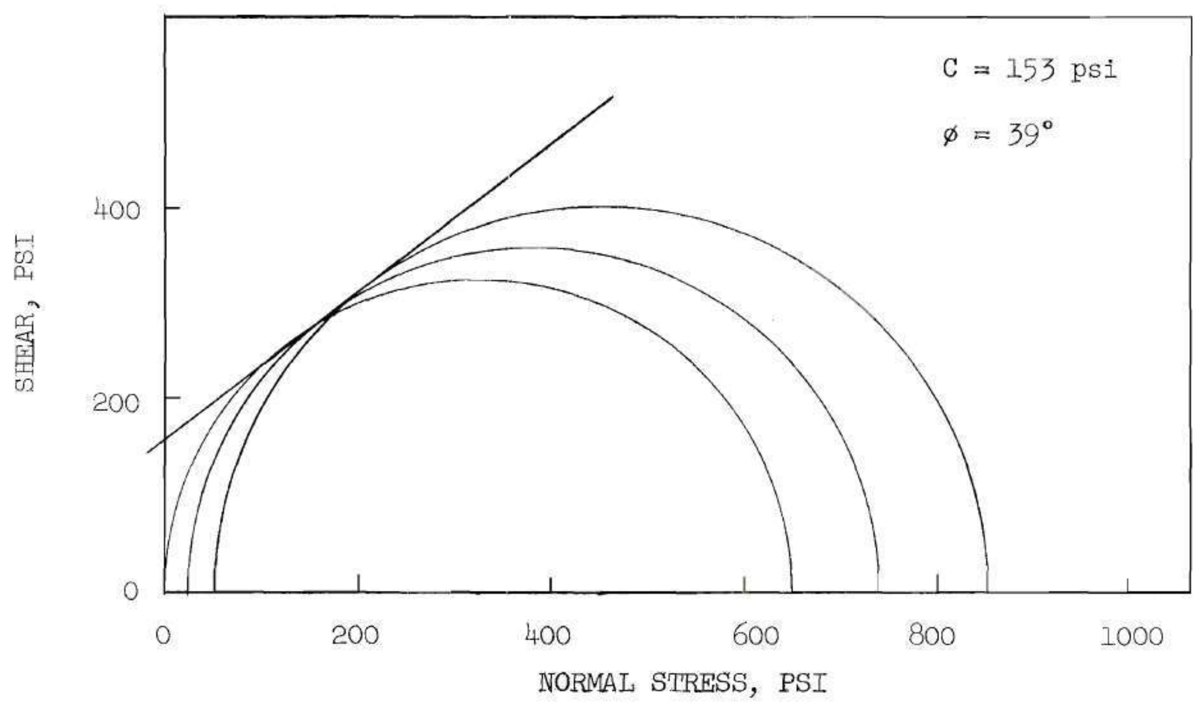

Figure 45. Mohr's Diagram for Soil IV with 15% Portland Cement.

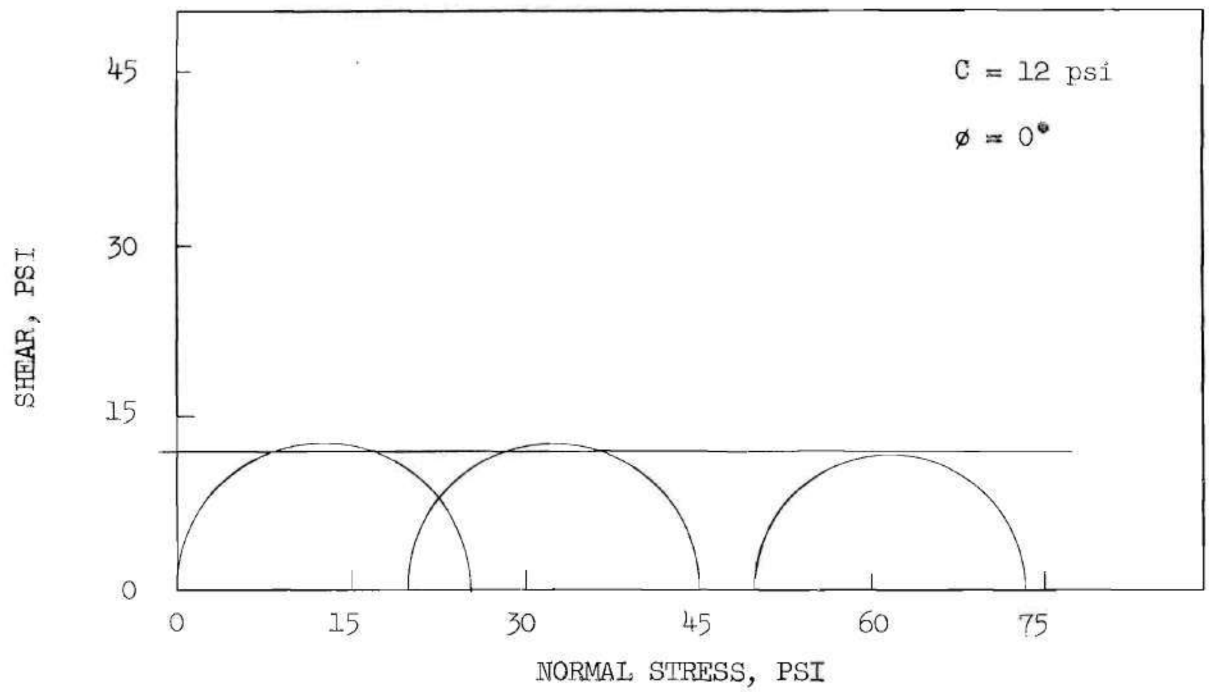

Figure 46. Mohr's Diagram for Soil V with no Admixture.

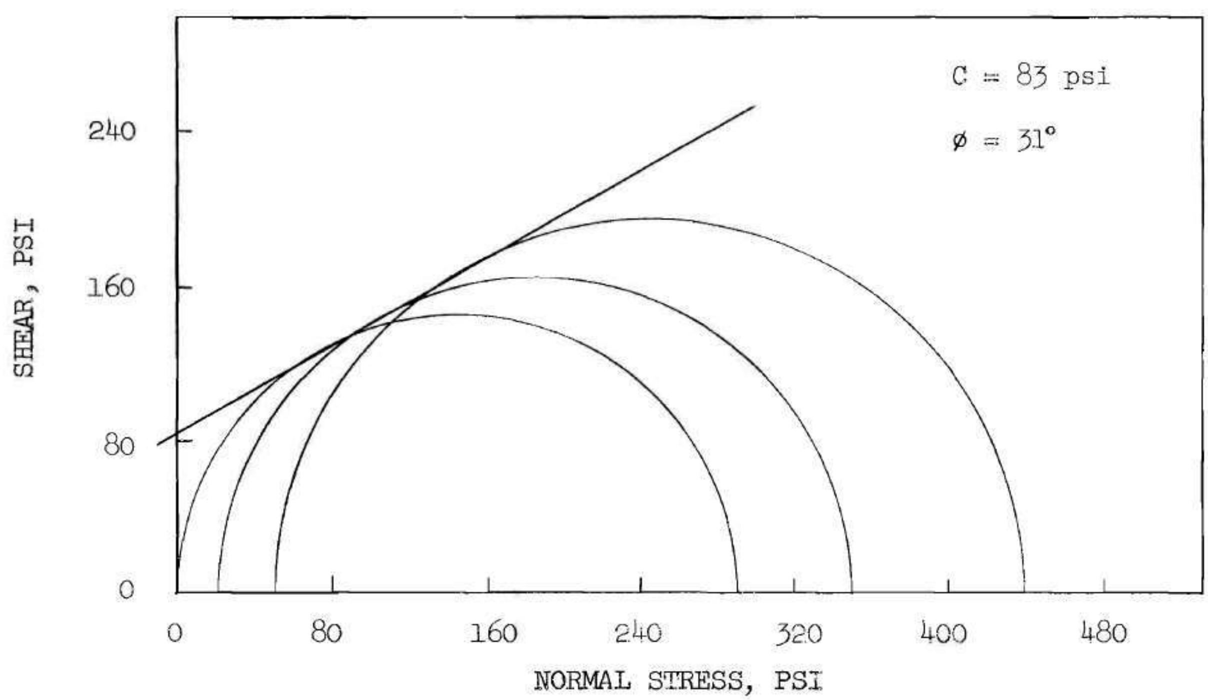

Figure 47. Mohr's Diagram for Soil V with 6% Portland Cement.

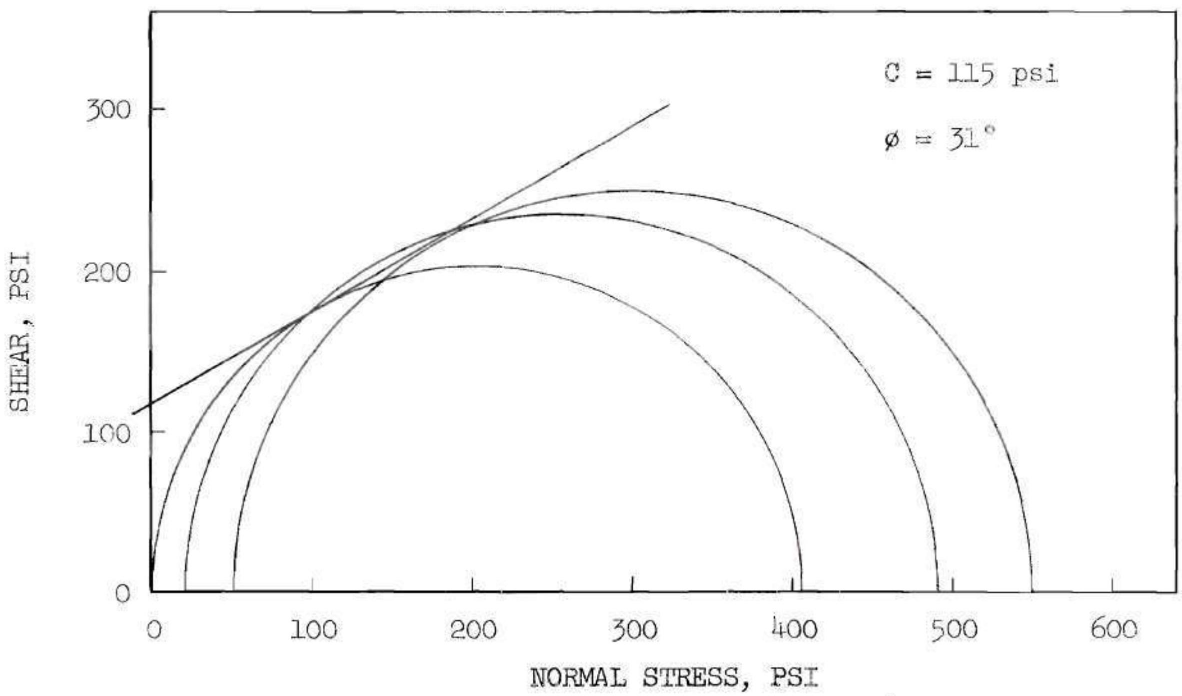

Figure 48. Mohr's Diagram for Soil V with 9% Portland Cement.

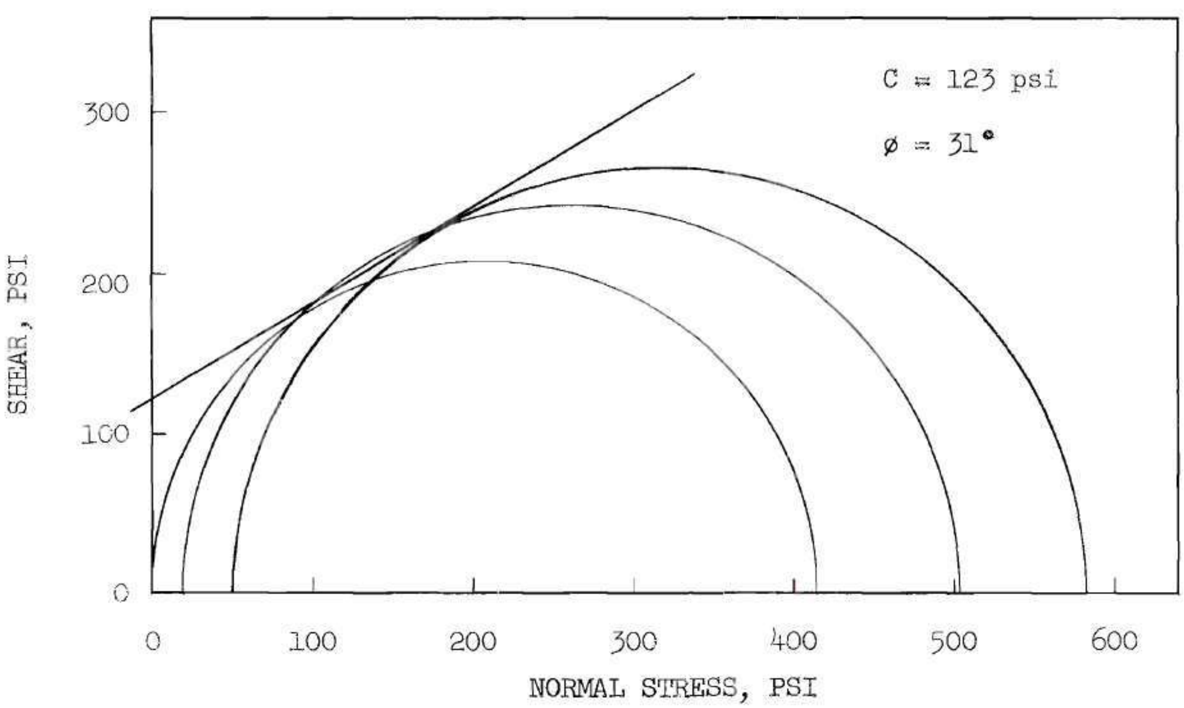

Figure 49. Mohr's Diagram for Soil V with 12% Portland Cement.

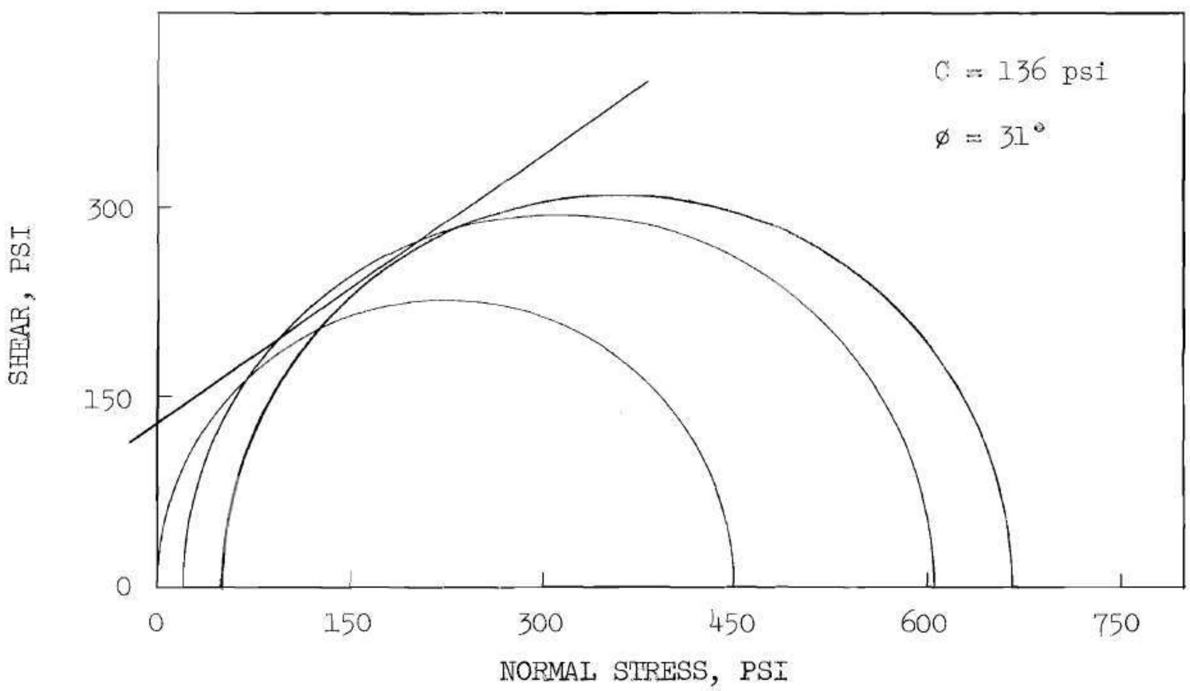

Figure 50. Mohr's Diagram for Soil V with 15% Portland Cement.

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